THE TELEPHONE HANDBOOK

BEING THE EIGHTH EDITION OF
THE "PRACTICAL TELEPHONE HANDBOOK"

BY

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COMPLETELY REVISED
BY

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PREFACE

The seventh edition of the Practical Telephone Handbook appeared in 1930, and consecutive editions up to that date had been revised and enlarged to keep pace with the developments that were continually taking place in telephony.

When Mr. Poole decided a few years ago that a further revision of the book was necessary, a very brief survey was sufficient to show that to treat the subject as generously as the previous issues had done, would entail a volume (or volumes) of great bulk and expense, which in due course would require still further revision and enlargement.

The time was considered a suitable one in which to break with the old system, and produce a new book which would attempt merely to provide a technical groundwork for students of telephony, to enable them to understand the principles of the subject, and to follow intelligently any developments that occurred; thus avoiding the need for constant revision.

The syllabuses of the City and Guilds of London Institute were revised in 1937, and this was a further inducement to commence on new lines, since by this date the scope of telephony had become so wide that only a knowledge of the basic C.B. and automatic systems in use in this country could be expected of second and third year students.

It is for these students that the book is chiefly written, and it covers the greater part of the material required for Grades I and II of Telephony and Transmission and Lines in the City and Guilds Institutes' examinations, so far as theoretical treatment of the subject is concerned.

In manual and automatic telephony, no particular manufacturer's system has been described, but the author has concentrated on the basic circuits of the standard Post Office schemes.

Since these sections were written, the new "2 000" type of automatic selector has been introduced, but the advent of the war will naturally retard the installation of new exchanges of this type, and it is expected that the descriptions of existing plant and circuits will suffice for examination purposes for a few years to come. Systems other than "Step-by-Step" automatic and C.B. manual have not been mentioned in view

of space considerations, but some of these, and the historical development of telephony, are well covered in the Seventh Edition of the PRACTICAL TELEPHONE HANDBOOK.

Most of the treatment is orthodox, but some is new, experience with first and second year students having indicated weaknesses in some hitherto accepted explanations. All diagrams have been specially drawn on a detached contact basis, and, it is hoped, in line with standard practice as regards conventions and symbols. It is the author's view that the subject has in the past been made needlessly complicated by the use of complex diagrams and the inclusion of non-essential facilities; and that if the basic facts are intelligently absorbed, the later assimilation of the refinements will follow easily and automatically.

No reference will be found in the present work to the "Director" system or to U.A.X. working, as these subjects would require as much space again for proper treatment, and are the concern only of the advanced student.

As each aspect of telephony now requires its own specialists, it is clearly impossible for the present edition to be described as "practical," hence the revision in title. Efficiency in practical work, especially in intricate adjustments, cannot be obtained by study from books, but the student with a good theoretical understanding of the subject should have no difficulty in obtaining a suitable course of practical instruction if he is required to undertake this class of work.

In the Transmission section, which has been prepared by Mr. W. Prickett, an effort has been made to simplify the theoretical treatment as far as possible, and in order to keep the size of the book to reasonable proportions, the sections on Overhead and Underground Construction have been omitted, since the Seventh Edition contains sufficient information to enable the student to appreciate the obvious improvements of the last few years.

Developments in carrier telephony are particularly rapid, but with the basic theoretical processes described, there should be no difficulty in understanding the various new schemes as these are developed. It is considered that 2 V.F. signalling could better be dealt with under Automatic Telephony, and as the Grade II Syllabus does not include this item, reference to it has been omitted. Similarly, no mention has been made of radio telephone links, as these are covered in treatises on Radio Communication. There is little that can become obsolete

in this section, but rapid improvements in valve, filter, and cable technique will necessitate continual reference to current literature on the subject if the student desires to be up to date.

The Engineer-in-Chief of the British Post Office has kindly given permission for the publication of information relating to systems in use in this country, and the various manufacturers whose names will be found associated with the illustrations have provided photographs or blocks for this purpose. Special thanks are due to Messrs Siemens in this connection.

Mr. Poole has approved the subject-matter, and his experience of telephony, extending over the whole of its period of development, has been of the greatest value in preparing the new edition.

N. V. KNIGHT.

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SYMBOLS AND ABBREVIATIONS

Physical

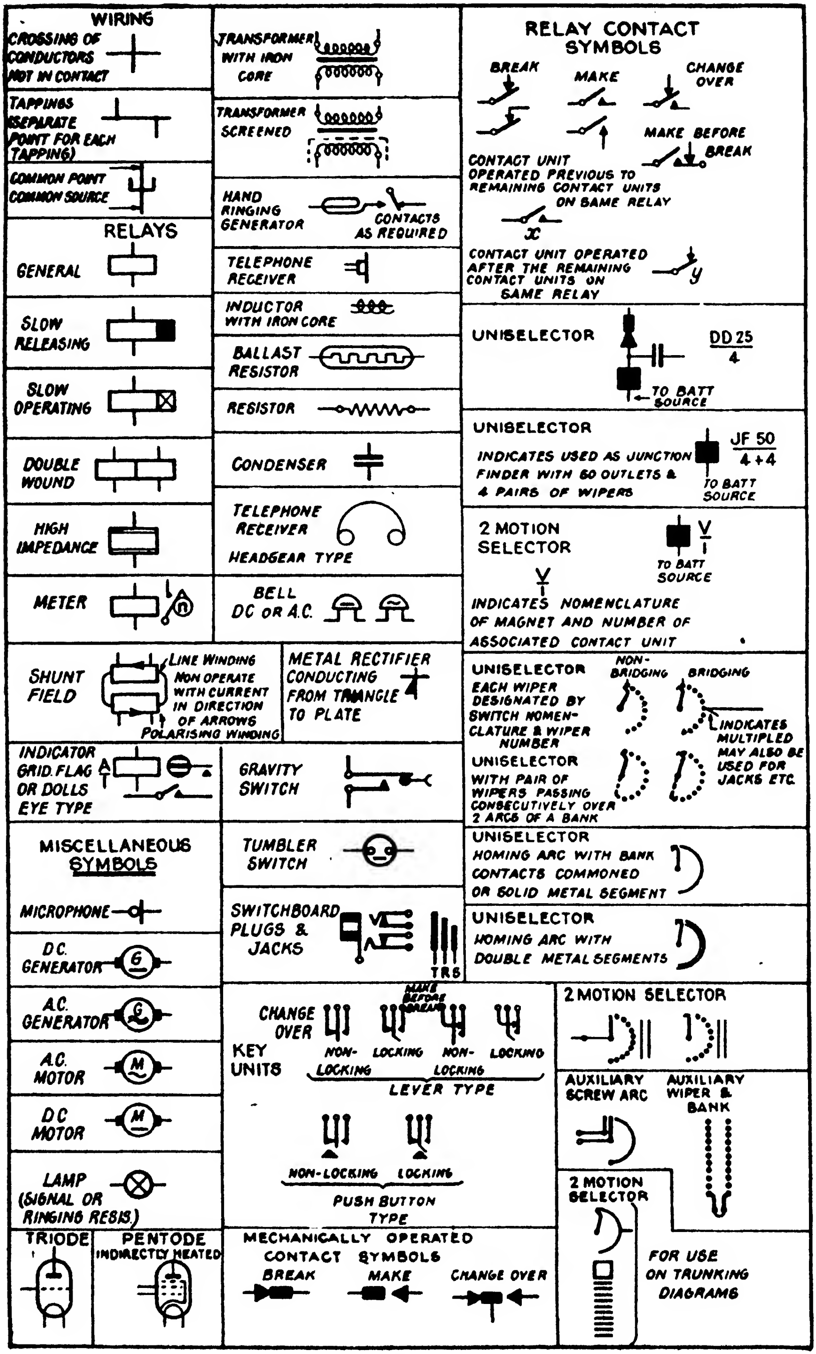
x	Distance	λ	Wave length
l	Length	r	Ratio
s, D	Spacing distance	d	Radius
T, t	Time	M, m	Coefficients
S	Velocity	A, B, C, D, a, n, k, c	Constants

Electrical

V, v	Voltage	$\omega = 2\pi f$	Pulsatance
I, i	Current	$Z, Z/\phi$	Impedance
R	Resistance	X	Reactance
L	Inductance	A	Admittance
G	Leakance	W	Power
C	Capacitance	ϕ	Phase angle
f	Frequency	ψ	Phase difference

Telephonic

$P = \beta + j\alpha$	Propagation constant
β	Attenuation constant
α	Phase constant
$a = \alpha l$	Phase change
f_c	Critical frequency
ω_c	Critical pulsatance
Z_0	Characteristic impedance
$\theta = Pl$	Propagation length
db.	Decibel
S.C.E.	Standard cable equivalent
T.E.	Transmission equivalent
T	Transmission time
τ	Transitory period


WIRING
CROSSING OF CONDUCTORS NOT IN CONTACT
TAPPINGS SEPARATE POINT FOR EACH TAPPING)
COMMON POINT COMMON SOURCE
RELAYS
GENERAL
SLOW RELEASING
SLOW OPERATING
DOUBLE WOUND
HIGH IMPEDANCE
METER
SHUNT FIELD
LINE WINDING NON OPERATE WITH CURRENT IN DIRECTION OF ARROWS
POLARISING WINDING
INDICATOR GRID FLAG OR DOLLS EYE TYPE
MISCELLANEOUS SYMBOLS
MICROPHONE
D.C. GENERATOR
A.C. GENERATOR
A.C. MOTOR
D.C. MOTOR
LAMP (SIGNAL OR RINGING RESIS.)
TRIODE
PENTODE INDIRECTLY HEATED
TRANSFORMER WITH IRON CORE
TRANSFORMER SCREENED
HAND RINGING GENERATOR
CONTACTS AS REQUIRED
TELEPHONE RECEIVER
INDUCTOR WITH IRON CORE
BALLAST RESISTOR
RESISTOR
CONDENSER
TELEPHONE RECEIVER HEADGEAR TYPE
BELL DC OR A.C.
METAL RECTIFIER CONDUCTING FROM TRIANGLE TO PLATE
GRAVITY SWITCH
TUMBLER SWITCH
SWITCHBOARD PLUGS & JACKS
T R S
KEY UNITS
CHANGE OVER
MAKE BEFORE BREAK
NON-LOCKING
LOCKING
NON-LOCKING
LOCKING
LEVER TYPE
NON-LOCKING
LOCKING
PUSH BUTTON TYPE
MECHANICALLY OPERATED CONTACT SYMBOLS
BREAK
MAKE
CHANGE OVER
RELAY CONTACT SYMBOLS
BREAK
MAKE
CHANGE OVER
MAKE BEFORE BREAK
CONTACT UNIT OPERATED PREVIOUS TO REMAINING CONTACT UNITS ON SAME RELAY
x
CONTACT UNIT OPERATED AFTER THE REMAINING CONTACT UNITS ON SAME RELAY
y
UNISELECTOR
DD 25 / 4
TO BATT SOURCE
UNISELECTOR
INDICATES USED AS JUNCTION FINDER WITH 60 OUTLETS & 4 PAIRS OF WIPERS
JF 50 / 4+4
TO BATT SOURCE
2 MOTION SELECTOR
V / I
TO BATT SOURCE
Y
INDICATES NOMENCLATURE OF MAGNET AND NUMBER OF ASSOCIATED CONTACT UNIT
UNISELECTOR
EACH WIPER DESIGNATED BY SWITCH NOMENCLATURE & WIPER NUMBER
NON-BRIDGING
BRIDGING
INDICATES MULTIPLED MAY ALSO BE USED FOR JACKS ETC.
UNISELECTOR
WITH PAIR OF WIPERS PASSING CONSECUTIVELY OVER 2 ARCS OF A BANK
UNISELECTOR
HOMING ARC WITH BANK CONTACTS COMMONED OR SOLID METAL SEGMENT
UNISELECTOR
HOMING ARC WITH DOUBLE METAL SEGMENTS
2 MOTION SELECTOR
AUXILIARY SCREW ARC
AUXILIARY WIPER & BANK
2 MOTION SELECTOR
FOR USE ON TRUNKING DIAGRAMS

THE TELEPHONE HANDBOOK

CHAPTER I

ALTERNATING CURRENT THEORY

CONSIDER a circuit in which direct current from a battery is reversed in direction through plain resistance as shown in the diagram. If the reversals are carried out uniformly at a fixed rate an alternating current of special form will be produced. The value of this current at any instant is shown by means of a graph plotted on a time base, and, in the example taken, one complete reversal is effected in $\frac{1}{5}$ sec. or, in other words, five complete reversals per second take place (Fig. 1). The

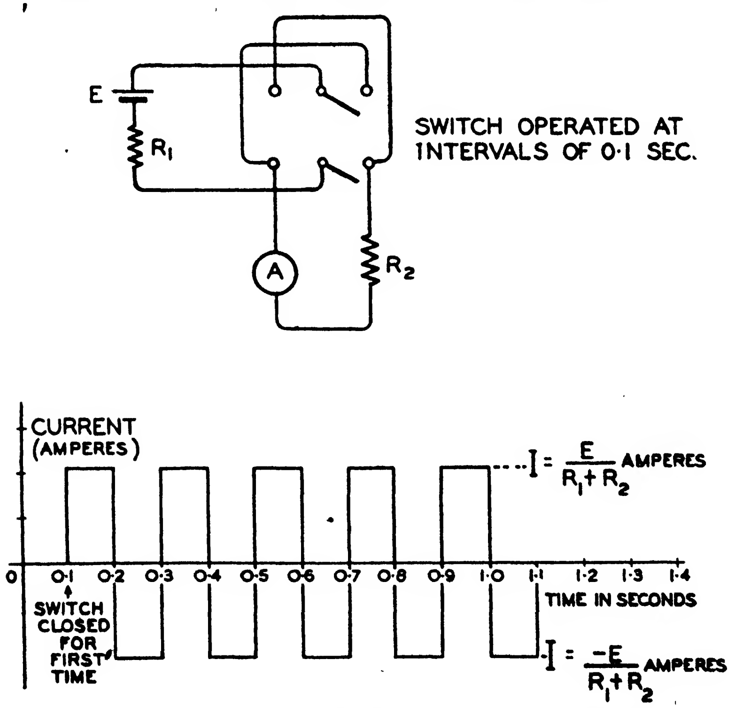


FIG. 1. PRODUCTION OF SIMPLE ALTERNATING CURRENT

resultant alternating current is then said to have a *frequency* of five cycles per second. The frequency of alternating currents used in telephony is generally understood to be in cycles per second and is indicated by the symbol f (or $\sim$).

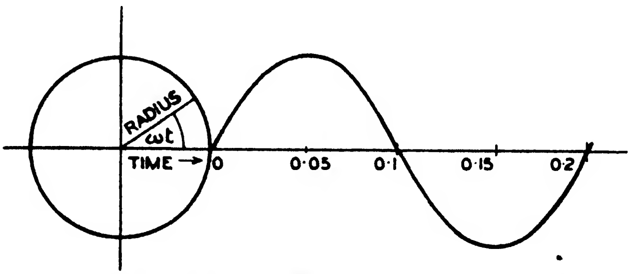


FIG. 2. SINE WAVE PRODUCED BY PROJECTION OF A RADIUS ROTATING FIVE TIMES PER SECOND

If instead of the battery a special form of generator is used, consisting of a single turn of wire mounted on an axis between two magnet poles of opposite polarity, the induced e.m.f. will

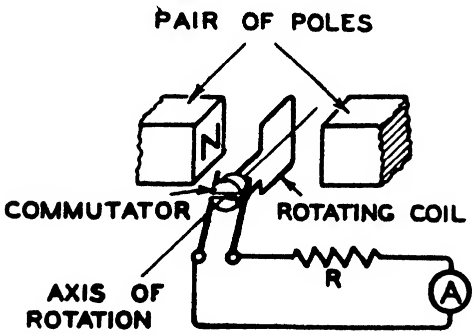


FIG. 3. ELECTRICAL CIRCUIT TO PRODUCE CURRENT OF FORM SHOWN IN FIG. 2 WHEN COIL IS ROTATED FIVE TIMES PER SECOND

be reversed in direction every half-revolution, but as the rate of cutting lines of magnetic force (on which the value of the induced e.m.f. depends) will vary with the position of the coil in the field, the e.m.f. will rise gradually from zero to a maximum value, and fall to zero again every half-cycle (Figs. 2 and 3).

Plotted on a time base as before, with the coil rotating five times each second, an alternating current of the same frequency is produced, but of different wave form. The shape of the wave is now nearly sinusoidal, and it is with this wave form that problems in telephony are usually concerned. The curve may be produced artificially by plotting the projection of the rotating radius on a time base. It will be noted that the projection of the radius is proportional to the sine of the angle turned through at any instant, and its height is indicated for different values of time plotted horizontally. Thus for frequency of five cycles (or five complete revolutions of the radius) per second, each complete cycle occupies $\frac{1}{5}$ sec. along the time base.

Now the coil will turn through 360° (or 2π radians) in each revolution.

The angle turned through in one second is therefore $2\pi/\frac{1}{5}$ radians, or 2π times the number of revolutions per second.

Starting from the zero position, the e.m.f. is proportional to the sine of the angle turned through, and at one second from the start has a value proportional to the sine of $2\pi f$ radians; and at t sec. from the start it is proportional to the sine of $2\pi ft$ radians.

In telephony it is very desirable to know the e.m.f. and currents at any instant, and they could be expressed in the form $\sin 2\pi ft$ where t is any arbitrary instant and f is the frequency of the speech transmitted. Such an expression is cumbersome and the constant $2\pi f$ is written ω.

The expression $\sin \omega t$ therefore indicates the instantaneous value of e.m.f. or current which is varying at a frequency $f = \omega/2\pi$. ω is termed the *angular velocity* of the wave form. It is the number of radians per second through which the coil of the generator must revolve to produce alternating current of a frequency f cycles per sec.

The frequencies of speech currents dealt with in telephone practice vary from 250 to 3 000 cycles per sec. For broadcasting, the frequency range is from 30 to 8 000, and for commercial power purposes, 25 and 50 per sec.

As the value of the current and voltage is changing continuously, it is customary to take a mean value when making calculations.

Now the mean value of $\sin\theta$ for each half-cycle is

$$\frac{1}{\pi}\int_0^{\pi}\sin\theta\,d\,\theta.$$

$$=\left(\frac{-\cos\theta}{\pi}\right)_0^{\pi}$$

$$=2/\pi$$

$$=0{\cdot}636$$

Since the current and voltage vary in the same manner, and are alternately positive and negative during successive half-cycles, the mean value of either will be zero.

Thus, any electrical effects which are directly proportional to the strength of the current or voltage, will have a mean value of zero in an a.c. circuit.

The chemical effect of an alternating current is therefore inappreciable, and a *rectifier* must be associated with the circuit if chemical effects, such as battery charging, are desired.

The electromagnetic flux in a circuit is proportional to the current, and its mean value in an a.c. circuit is therefore zero. The attraction or pull of an electromagnet is, however, proportional to the square of the flux, being equal to $B^2a/8\pi$ dynes, where B is the value of the flux in gausses, and a is the area of the pole face in square centimetres.

Since, in telephony and most other branches of electrical science, the electromagnetic pull determines the power to be obtained from a piece of apparatus, it is the square of the current or voltage which is of most practical use, and this value is, of course, independent of the sign (positive or negative) of the quantity to be squared.

The heating effect of a current is also proportional to its value squared, and in order to secure uniformity with the direct current case, it is usual to express the magnitudes of alternating currents and voltages by their *r.m.s.* (*root-mean-square*) values, thereby allowing direct comparison with direct current of the same nominal magnitude.

For example, a direct current potential of 10 volts would be required to send a current of 2 amperes through a resistance of 5 ohms, and 20 watts would thereby be expended in heating the resistance.

An r.m.s. voltage of 10 volts a.c. would give exactly the same result, and it only remains therefore to find the relation between the r.m.s. and maximum values of alternating quantities, and the same power relations will hold good for either alternating or direct current.

If the r.m.s. value is squared, the "mean square" value will be obtained.

Now, the mean square value of sin θ is

$$\frac{2}{\pi}\int_0^{\frac{\pi}{2}} \sin^2\theta \,.\, d\theta \text{ (see Fig. 4)}$$

$$= \frac{2}{2\pi}\int_0^{\frac{\pi}{2}} (1 - \cos 2\theta)\, d\theta$$

$$= \frac{1}{\pi}\left(\theta - \frac{\sin 2\theta}{2}\right)_0^{\frac{\pi}{2}}$$

$$= \pi/2\pi$$

$$= \tfrac{1}{2}$$

The root mean square value is therefore $1/\sqrt{2}$ or 0·707.

The maximum value of sin θ is 1·0, and so r.m.s. values of alternating quantities are 0·707 of their maximum values. The mean and r.m.s. values of sin θ are shown on the graph of sin θ and $\sin^2\theta$, in Fig. 4.

If an alternating voltage is applied to a circuit containing only resistance, the current at any instant is given by dividing the e.m.f. by the resistance, i.e. the circuit obeys Ohm's law.

This state of affairs does not often occur in telephony, where alternating currents generally flow in circuits which have the properties of *Inductance* and *Capacitance*, as well as of *Resistance*.

These terms will first be defined, and then their influence on the behaviour of the current explained.

INDUCTANCE

Whenever the current flow in a circuit is varied, there is a corresponding change in the number of magnetic lines of force linked with that circuit. If the conductor is arranged so that the number of lines of force produced is large (this

may most conveniently be effected by winding the conductor in the form of a close-coiled helix) there will be large changes of flux when the current is altered.

Now the flux is linked with the conductor, and for every

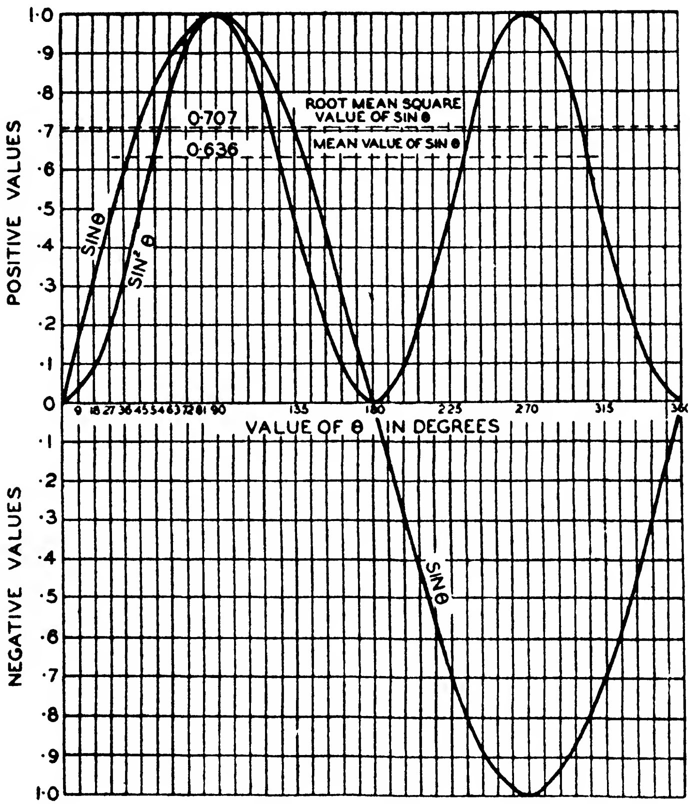


FIG. 4. VALUES OF SIN θ AND SIN² θ FOR A COMPLETE CYCLE

change in the former there is a corresponding e.m.f. induced in the latter. The direction of this induced e.m.f. is, by Lenz's law, such as to oppose the e.m.f. causing the current to flow. The increase or decrease in current is therefore retarded, in proportion to the change in flux linkages, and the circuit is said to exhibit the property of *inductance*.

The practical unit is the *henry* (abbreviation: H.), and a circuit possesses an inductance of one henry if an average e.m.f. of one volt is induced when the current flow varies at

the rate of one ampere per second (increase or decrease) in the circuit.

In d.c. circuits, the inductance is only of importance when the circuit is closed and opened.

On closing the circuit, the increase in the number of lines of force creates a *back e.m.f.* in the conductor, and the current, i amperes, at any instant t sec. after the current has commenced to flow, is given by the expression

$$i = \frac{E}{R}\left(1 - e^{-\frac{Rt}{L}}\right)$$

where i is the instantaneous current in amperes;

E is the applied voltage in volts;

R is the resistance of the circuit in ohms;

L is the inductance of the circuit in henries;

t is the time in seconds.

The equation is often called the 'Helmholtz' equation, and it will be seen on examination that the back e.m.f. at any instant is $Ee^{-Rt/L}/R$, which will be zero if t is very large, or if L is negligible as in the plain resistance circuit.

At a time $t = L/R$ sec., $e^{-Rt/L}$ becomes e^{-1} or $1/e$.

The instantaneous current is $i = \frac{E}{R}\left(1 - \frac{1}{e}\right)$

$$= \frac{E}{R}\left(\frac{e-1}{e}\right)$$

$$= 0{\cdot}632E/R.$$

This particular value of t is called the *time constant* of the circuit. It may be defined as the time taken for the current to reach 63·2 per cent of its final value.

In certain circuits the time is considerable, e.g. the field winding of an alternator may be of 100 henries inductance and 4 ohms resistance. The current would then take $100/4 = 25$ sec. to reach 62·3 per cent of its final value, and much longer to attain, say, 95 per cent of the ultimate figure at which it remains constant. Theoretically, the maximum value is never obtained until $t = \infty$, but if the relation between i and t is plotted, it will be seen that after a period $t = 4L/R$, the current is reasonably near its maximum, being, in fact, 98 per cent of that figure.

Energy Stored in an Inductance. The fact that the current in an inductive circuit does not rise at once to its final value indicates that energy is being absorbed in the circuit, and the amount involved can be arrived at as follows.

Suppose the current changes from zero to I amperes in t sec. The average rate of change is I/t amperes per sec., and by definition, the average back e.m.f. will be LI/t volts. Now the average value of the current is $I/2$ amperes, and the average rate of taking energy from the source is the product of the volts and amperes, or $LI^2/2t$ watts.

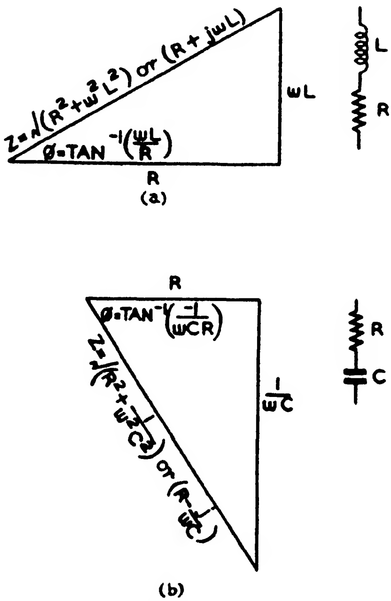


FIG. 5. IMPEDANCE VECTORS

The total energy absorbed in the t sec. will therefore be $(LI^2/2t) \times t$, or $\frac{1}{2}LI^2$ joules.

This energy is stored in the inductance as long as the current I flows. When the current is cut off, the energy is suddenly released, and appears as heat in an arc at the point of breaking the circuit, or is absorbed in a specially designed spark quench circuit, consisting generally of a condenser and resistance placed across the inductance.

Current Lag in an Inductance. When a constant e.m.f. is applied to an inductance, it has been shown that the current takes time to reach a steady value, or, in other words, the current lags behind the applied voltage. When alternating currents are concerned, the lag is still present, but since the applied voltage varies sinusoidally, the current behaves in similar fashion, but at a constant interval after it, depending on the ratio of inductance to resistance in the circuit. This lag never exceeds a quarter of a cycle of the alternating e.m.f., and only reaches that value if there is no resistance present. In the vector diagram (Fig. 5) it will be observed that the ratio of

resistance to inductance directly determines the angle of lag of the current. The term *impedance* is used to express the opposition of a circuit containing resistance as well as inductance and capacitance, the opposition of the last two being termed *reactance.* The combination of resistance and reactance in a circuit therefore represents its impedance to alternating current. The reactance of a circuit of L henries inductance at a frequency f cycles per sec. is $2\pi fL$ ohms, or ωL ohms. If the resistance of the circuit is R ohms, the impedance is $\sqrt{(R^2 + \omega^2 L^2)}$ ohms, and the angle of lag of the current is $\tan^{-1} (\omega L/R)$. Hence, if R is zero, the angle is 90°.

The reactance limits the value of the current in the inductance to $E/\omega L$ amperes, where E is the alternating voltage applied to the circuit. Where direct current is concerned, $\omega = 0$, and the current would become infinite in time, as would be expected with no resistance present.

CAPACITANCE

When a current of I amperes flows for t sec. along a conductor, a charge of It coulombs is said to have passed through the circuit. Some of this charge may remain on the conductor by virtue of its capacitance. If the conductor is favourably shaped, e.g. into a large plate, and placed adjacent to a similar conductor in the return portion of the circuit, the amount of charge stored is considerable, and such a device is termed a condenser. The unit of capacitance is the *farad* (abbreviation: *F.*), and a condenser has a capacitance of one farad if a potential of one volt applied to its terminals results in a charge of one coulomb in the condenser.

Such a unit is inconveniently large for normal use, and the *microfarad* (abbreviation: $\mu F.$, Greek small μ (mu) signifying 'millionth') or one millionth of a farad, is the unit in common usage. One volt applied to a condenser of capacitance one microfarad would result in a charge of one *micro coulomb.*

This definition of the unit of capacitance establishes the fundamental relation—

$$Q = EC$$

where Q is the charge in coulombs in a condenser of capacitance C farads, when E volts are applied.

If the condenser is charged through a resistance R ohms in series, the current i at any instant t is given by the formula $i = (E/R)e^{-t/CR}$, and when discharging under the same conditions, $i = (E/R)e^{-t/CR}$. It will be seen that the initial value is E/R, and the final value zero. If the value of charging current is plotted against the time, the curve obtained will be seen to be the inversion of that obtained for the rise of current in an inductance. Consequently, for a suitable combination of inductance and capacitance in a circuit, a non-reactive effect can be obtained. The particular conditions will be apparent later.

Energy Stored in a Capacitance. Assume a voltage E to be applied to a discharged condenser of C farads capacitance, and let the time taken to complete the charging be t sec. The mean value of the charging current will be Q/t amperes, and the mean voltage across the terminals $E/2$ volts. The mean rate of taking energy from the source is therefore $(E/2)\ (Q/t)$ watts, and the total energy for the period t sec. is obviously the product of watts and time, or $EQ/2$ joules. But $Q = EC$, and the energy is therefore $\frac{1}{2}E^2C$ joules, and this will be stored in the condenser, to be released on its discharge.

It is interesting to note that the energy dissipated in the circuit during the charging of the condenser is also $\frac{1}{2}E^2C$ joules, since if the series resistance of the charging circuit is R ohms, the mean value of the charging current flowing through R is Q/t amperes, as the condenser is in series. The mean voltage across the condenser has been shown to be $E/2$ volts, and therefore the mean voltage across R is $(E - \frac{1}{2}E)$, or $E/2$ volts. The mean number of watts dissipated in the product of these is $EQ/2t$ watts, and putting $Q = EC$, and multiplying by t to obtain the energy, the joules expended equal $EC^2/2$. This result may be confirmed by integration.

The voltage across the condenser terminals at any instant during charging is obtained by dividing the charge by the capacitance, and increases logarithmically with the time. Since a charging current must necessarily flow, therefore, in order to produce an opposing e.m.f., it follows that the e.m.f. lags behind the current, or, in other words, the current leads the voltage.

It is customary to speak of a condenser taking a 'leading' current, and in alternating current working advantage is taken

of this feature to correct the lagging of the current in inductive circuits, by placing a condenser of the appropriate value in series.

When an alternating voltage is applied to a condenser, the charging current flows during each half-cycle, reversing its direction in sympathy with the reversal of voltage, but in advance of it to an extent determined by the remaining properties of the circuit. As in the case of the inductance, the maximum angle of phase difference between current and voltage is 90°.

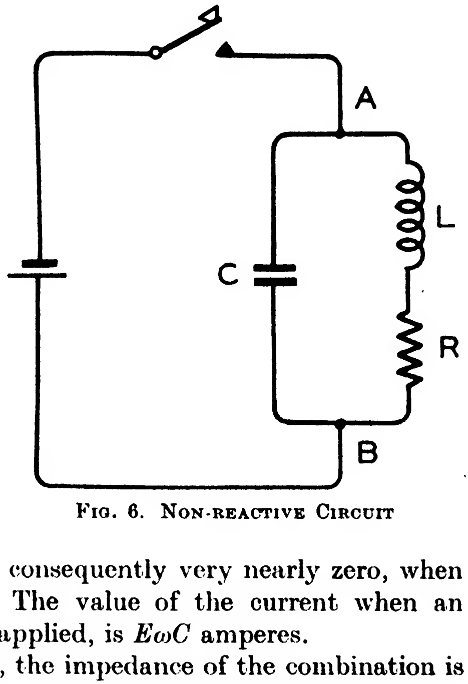


FIG. 6. NON-REACTIVE CIRCUIT

The reactance of a condenser is $1/\omega C$ ohms, where $\omega = 2\pi f$ (f = frequency of applied alternating potential), and is consequently very nearly zero, when either ω or C is large. The value of the current when an alternating voltage E is applied, is $E\omega C$ amperes.

With R ohms in series, the impedance of the combination is $\sqrt{(R^2 + 1/\omega^2 C^2)}$ ohms, and the angle of lead of the current is $\tan^{-1}(1/\omega CR)$. Hence, if R is zero the angle is 90°.

Non-reactive Circuit. Consider the circuit shown in Fig. 6. When the key is closed, the current rises to a final value $I = E/R$ amperes. The energy stored in the inductance is then $\frac{1}{2}LI^2$ joules, and in the capacitance $\frac{1}{2}CE^2$ joules. When the key is released, there will be no dissipation of energy at the key contacts if the released energy from the condenser neutralizes that from the inductance;

i.e. $\qquad \frac{1}{2}CE^2 = \frac{1}{2}LI^2$

But since $I = E/R \qquad \frac{1}{2}CE^2 = \frac{1}{2}LE^2/R^2$,

and $\qquad C = L/R^2$, or $L = CR^2$.

This is the condition for a non-reactive network.

Combination of Inductance and Capacitance. In circuits where the inductive reactance ωL is equal to the capacitive reactance $1/\omega C$, the current is in phase with the voltage, even though resistance may be in series.

Putting $\qquad \omega L = 1/\omega C$

then $\qquad \omega^2 = 1/LC$

or $\qquad \omega = 1/\sqrt{(LC)}$,

and the frequency of the alternating current must be $1/2\pi\sqrt{(LC)}$. Such a circuit is said to be *resonant* at the particular frequency. For any condition other than where the reactances are equal, the current is out of phase with the voltage, and its magnitude must be calculated with due regard for the phase angle.

Vector Diagrams. The relations between the current and voltage are best shown by means of vector diagrams. In such a diagram (Fig. 7), the usual axes XOX', YOY' are used, with the following conventions—

The point of intersection, O, is the zero for the horizontal and vertical scales, and the centre of rotation for the radius vector, OP.

The angle between OP and OX is the angle of rotation of the radius vector, the positive direction being *anti*clockwise. Consequently, when OP coincides with OX, the normal 'in phase' conditions obtain.

Distances measured to the *right* of YOY' are reckoned *positive*

,,	,,	,,	*left* of YOY'	,,	,,	*negative*
,,	,,	,,	*above* XOX'	,,	,,	*positive*
,,	,,	,,	*below* YOY'	,,	,,	*negative*

The radius vector is always positive.

In setting out the electrical behaviour of a circuit containing inductance and resistance, or capacitance and resistance, in series, or all three, the following procedure is adopted.

(*a*) The voltage drop IR, in the resistance, is set out along OX on a suitable scale.

(*b*) From the point A thus obtained, the voltage drop in the reactance, $I\omega L$, is set out in a direction 90° removed from the voltage drop IR. In the first case, where inductance and resistance are present, the line OP indicates the magnitude of

the resultant voltage drop, the phase angle of which is given by the extent of rotation from the zero position along OX.

(c) The magnitude can be calculated from the known relation between the sides of a right-angled triangle,

i.e. $$OP^2 = OA^2 + AP^2,$$

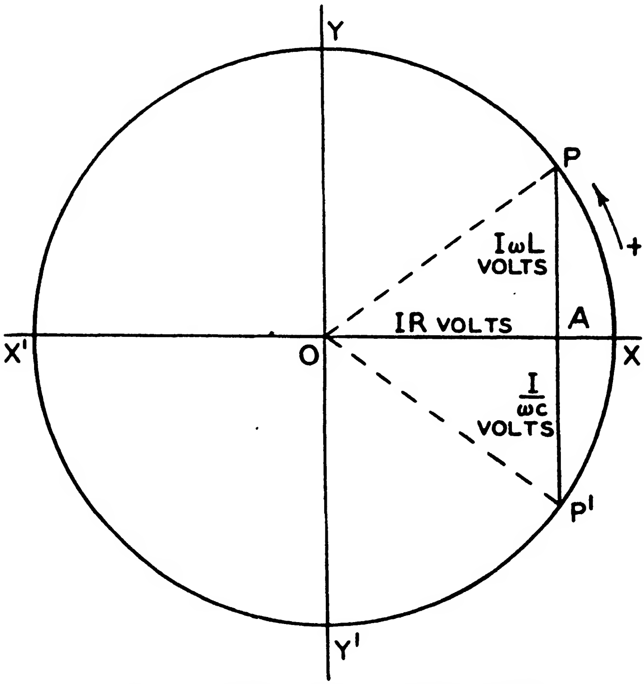


FIG. 7. CURRENT AND VOLTAGE VECTORS

or, if OP is termed the *total voltage drop*, IZ ohms,

$$I^2Z^2 = I^2R^2 + I^2\omega^2L^2$$

or $$Z = \sqrt{(R^2 + \omega^2L^2)}$$

and the angle AOP is seen to be $\tan^{-1}(AP/OA)$ or $\tan^{-1}(\omega L/R)$.

(d) Where the circuit contains only capacitance and resistance, OA will represent the voltage drop in phase with the current and AP' the voltage drop 90° in advance. OP' is the resultant drop, and its magnitude is $\sqrt{(I^2R^2 + 1/\omega^2C^2)}$, and the impedance Z will be $\sqrt{(R^2 + 1/\omega^2C^2)}$ at an angle $\tan^{-1}(1/\omega CR)$.

As the angle is obtained by 'clockwise' rotation from OX, it will be a negative, or 'leading' angle.

(*e*) It will be noted that in the event of ωL being equal to $1/\omega C$, $AP = AP'$, and the two values of Z are identical, the angles being equal in magnitude but opposite in sign.

(*f*) In cases where both types of reactance are present, the value AP of ωL is set out first, in the upwards direction vertically from OX, and the value, PP', of $1/\omega C$ is set out vertically downwards from the point P. Thus, if $1/\omega C$ is less than ωL, the point P' is above OX, and the reactance is positive, i.e. the current lags behind the voltage. Where $1/\omega C$ is greater than ωL, P' will be below OX, and the reactance will be negative.

(*g*) The value of Z will be equal to $\sqrt{[R^2 + (\omega L - 1/\omega C)^2]}$. and the angle will be $\tan^{-1} \dfrac{\omega L - 1/\omega C}{R}$, which will give a negative angle if ωL is less than $1/\omega C$.

(*h*) In the cases where there is no resistance, the angle is $\tan^{-1} \dfrac{\omega L - 1/\omega C}{0} = \tan^{-1} \pm$, or $\pm 90°$, depending on which reactance is the greater. Thus it can be seen that in the simple series circuit, the quadrants YOX' and $X'OY'$ are never occupied. When complex circuits are analysed, it will be found that OP can be rotated through more than 90° under certain conditions, but these conditions will not be explored at present.

Current, Voltage, and Power in A.C. Circuits. In the examples taken, the current has been regarded as the starting point, and the phase of the voltage calculated therefrom. The power in a d.c. circuit is calculated by finding the product of the volts and amperes, but in alternating current power calculations the relative phases of these components must be taken into account.

If the current is considered as at zero phase angle, and the voltage at an angle ϕ thereto, then the proportion of the voltage V in phase with the current can be seen to be $V \cos \phi$, and the proportion 90° out of phase is $V \sin \phi$. The power in the circuit is therefore $VI \cos \phi$, and if the angle ϕ is zero, the power is a maximum, since $\cos \phi$ is unity.

Cos ϕ is termed the *power factor* (abbreviation: p.f.) of the

circuit, and is expressed as its numerical equivalent; i.e. if the angle ϕ is 0°, the power factor is unity,

at 30°,	,,	,,	,,	,,	0·866,
at 45°,	,,	,,	,,	,,	0·707,
at 60°,	,,	,,	,,	,,	0·500,
at 90°,	,,	,,	,,	,,	0·000.

In the latter case, the current in the circuit has no component of the voltage in phase with it, and is known as *wattless* current. Such current can only flow in a circuit which possesses negligible resistance.

Mathematical Representation of Vectors. It is often inconvenient to draw a vector diagram if the behaviour of a particular circuit is to be analysed, and instead, the components of the circuit are represented in their correct phase relationship by means of the symbol j (which actually stands for the square root of minus one).

To take the circuit with inductance L in series with resistance R as an example, the voltage in phase with the current is IR, where I is the current, and the voltage 90° ahead of this is $I\omega L$. The prefix j is placed in front of the latter to indicate rotation through a positive angle of 90°. It is to be considered as a multiplying factor, i.e.

Multiplication by	j	rotates a vector	+	90°
,, ,,	j^2	,, ,,		180°
,, ,,	j^3	,, ,,		270°
,, ,,	j^4	,, ,,		360°
,, ,,	$-j$	,, ,,	$-$	90°, etc.

This is shown in the diagram (Fig. 8) where two linear quantities A and B are added—

(*a*)	B in phase with A,	or	$A + B$
(*b*)	B 90° behind A,	,,	$A + jB$
(*c*)	B 180° ,, A,	,,	$A + j^2B$
(*d*)	B 270° ,, A,	,,	$A + j^3B$
(*e*)	B 360° ,, A,	,,	$A + j^4B$

Now it can be seen from the diagram that (*c*) is equal to $A - B$, and (*e*) is equal to $A + B$.

Hence, $\quad j^2 = -1$

and $\quad j^4 = 1$

The only value for j which satisfies the expressions therefore is that

$$j = \sqrt{-1}$$

and it is the remarkable properties of this convenient symbol that allow alternating current circuits to be analysed in a straightforward mathematical manner.

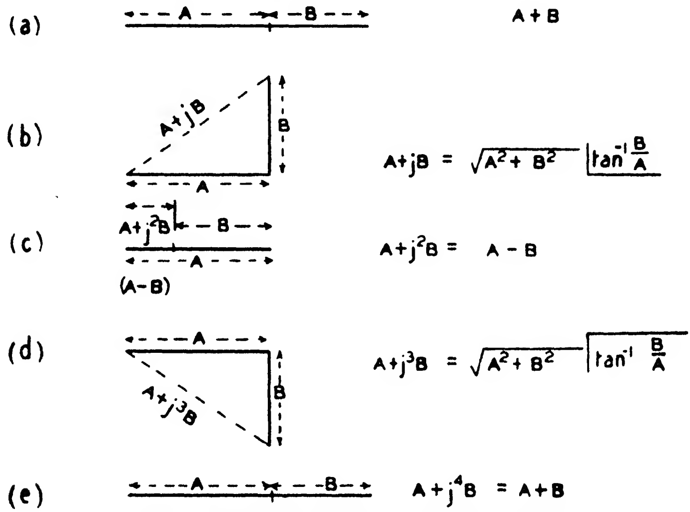


FIG. 8. ADDITION OF LINEAR QUANTITIES

The voltage in a circuit containing inductance and resistance in series is therefore $IR + jI\omega L$, or $I(R + j\omega L)$ volts.

For a circuit containing resistance and capacitance in series, $V = I(R - j/\omega C)$ volts, the negative sign indicating the leading angle of the current. With inductance, resistance, and capacitance in series, $V = I[R + j(\omega L - 1/\omega C)]$ volts. As before, when $\omega L = 1/\omega C$, the j term vanishes. The reactance of an inductance is therefore $j\omega L$ ohms, and that of a condenser $-j/\omega C$ ohms. Hence the impedance of any circuit can be written down by examination of the component parts. As an example, the impedance of the circuit shown in Fig. 6 between the points A and B is—

$$\frac{(R + j\omega L)(-j/\omega C)}{R + j(\omega L - 1/\omega C)} \text{ ohms.}$$

A method for simplifying such an expression will now be considered.

Complex Quantities. An expression such as the foregoing, containing terms multiplied by the operator j, is known as *complex*. Such an expression can always be separated into its 'real' and 'unreal' parts (i.e. ordinary terms, and those containing j), and this separation is essential if the resultant expression is to be correctly interpreted.

In the general case, two complex expressions, $(a + jb)$ and $(c + jd)$, can be combined as follows—

(i) $(a + jb) + (c + jd)$

$= (a + c) + j(b + d)$

$= x + jy$ where $x = (a + c)$ and $y = (b + d)$.

(ii) $(a + jb) - (c + jd)$

$= (a - c) + j(b - d)$

$= (x + jy)$ where $x = (a - c)$ and $y = (b - d)$.

(iii) $(a + jb)(c + jd)$

$= ac + jad + jbc + j^2bd$

$= ac - bd + j(ad + bc)$

$= (ac - bd) + j(ad + bc)$

$= x + jy$ where $x = (ac - bd)$ and $y = (ad + bc)$.

(iv) $\left.\dfrac{(a + jb)}{(c + jd)}\right\}$ multiply numerator and denominator by $(c - jd)$

$$= \frac{(a + jb)(c - jd)}{(c + jd)(c - jd)}$$

$$= \frac{ac - jad + jbc - j^2bd}{c^2 - j^2d^2}$$

$$= \frac{(ac + bd) - j(ad - bc)}{c^2 + d^2}$$

$$= \frac{(ac + bd)}{(c^2 + d^2)} - \frac{j(ad - bc)}{(c^2 + d^2)}$$

$$= x - jy, \text{ where } x = \frac{(ac + bd)}{(c^2 + d^2)} \text{ and } y = \frac{(ad - bc)}{(c^2 + d^2)}.$$

The above will cover all the variations likely to be met in a.c. questions, provided the necessary substitutions are made. For example, $(a + jb)^2 = (a + jb)(a + jb)$, and from (iii), this is equal to $(a^2 - b^2) + 2jab$.

CHAPTER II

TELEPHONE INSTRUMENT CIRCUITS

Sound. Any moving body makes a 'sound,' and the nature of its movements determines the character of the sound produced. Large movements produce louder noises than small movements, and up to a certain limit, the quicker the movement, the more intense the sound. Regular movements of an object are termed *vibrations*, and these may be simple or complex, as explained in Chapter XIV. What is of most importance is that there must be some medium to convey the movements of the source of sound to the drum of the listener's ear. It can be demonstrated that no noise is emitted from vibrating objects in a vacuum chamber, because there is no substance to communicate the vibrations to the ear. It is found that the more dense the medium, the more readily are the vibrations communicated; but in telephony the only medium to be considered is air, through which sound is known to travel at a speed of about 1 100 ft. per sec.

The vibrations of the source of sound are communicated to the surrounding air, and cause variations in pressure in the latter. These variations in pressure travel outwards from the source in much the same way as ripples in water which has been suddenly disturbed, i.e. there is no continuous flow of water, but a wave is propagated at a constant speed but with diminishing amplitude as it travels away from the source.

The human voice consists of a series of rapid complex vibrations, which produce correspondingly complex changes of pressure in the air. These changes of pressure, on being communicated to the ear drum, are translated by a system of nerves, which signal the speech to the brain.

Telephony is simply the science of extending the radius of communication, by translating the variations in air pressure into corresponding variations in electrical pressure, conveying the latter to any required point by means of electrical conductors, and then translating them back again into variations of air pressure so as to be intelligible to the listener.

The device used in telephony to detect any change in air

pressure is termed a *diaphragm.* Changes of pressure on one side only of a diaphragm (a thin metal disc in this instance) cause movements of the latter, and these movements are utilized to generate an electromotive force, the whole apparatus being termed a transmitter.

At the receiving end, the same electromotive forces in the circuit are employed to move a similar diaphragm, which reproduces changes in air pressure more or less similar to those actuating the transmitter.

Changes in pressure are measured in dynes per square centimetre, and the intensity of a sound can be referred to in these units.

Interconnection of Instruments. Individual transmitters and receivers could be connected together by separate circuits as required, but this scheme would be both cumbersome and expensive. The transmitting and receiving equipment, together with the signalling apparatus, are combined together in one instrument usually referred to as a *telephone.* Individual telephones are connected to a central switching point, termed an *exchange,* which may be automatic in action, under the direction of subscribers' signals, or be controlled by operators, in which case the connections between subscribers' lines are set up manually (Fig. 9).

The telephone exchanges themselves are connected together by a network of *junctions* and *trunks,* the term 'junction' being applied to an interconnecting route used mainly for the completion of calls set up in its immediate neighbourhood, and the term 'trunk' signifying a main communication channel between telephone centres in different parts of the country. The terms are somewhat elastic, and to a certain degree interchangeable.

Telephone Systems. There are many current systems of telephone switching, the simplest being the *magneto* system, in which calling and clearing signals are effected by magneto generators. A somewhat more elaborate scheme, utilizing a central battery at the exchange for signalling purposes, is referred to as the *C.B.S.* (*central battery signalling*) system. The most widely used, however, as the basis of manual and automatic networks, is the *C.B.* system, which is described in the following chapters. The term 'C.B.' is an abbreviation for

common battery, and implies that the whole of the energy used for speaking and signalling is derived from one secondary cell battery situated at the main exchange. Current for the sub-

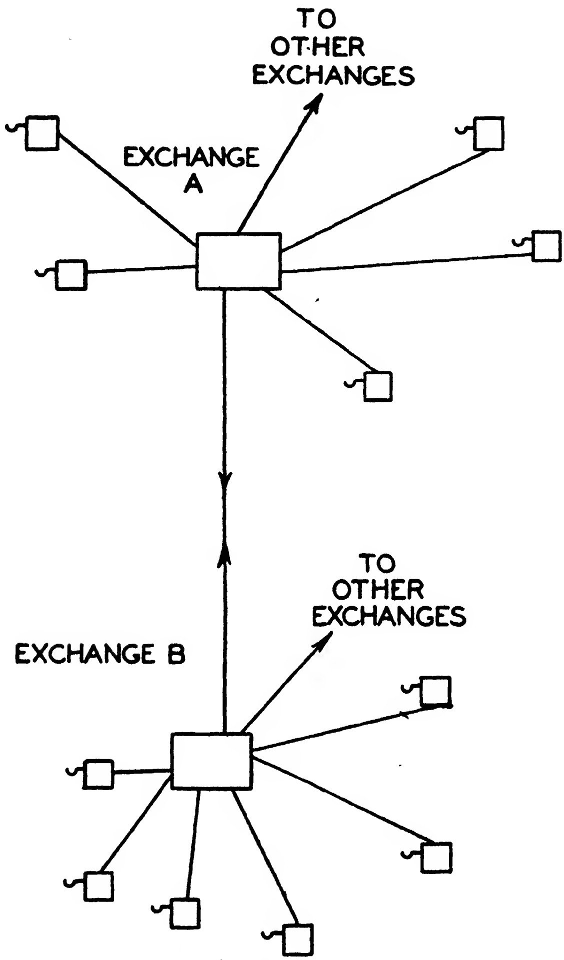


FIG. 9. INTERCONNECTION OF SUBSCRIBERS AND EXCHANGES

scribers' instruments is circulated via the ordinary overhead or underground lines. For circuits over which conversation takes place, twisted pairs (two or four wires) are always used, whereas for signalling purposes, single wires may be employed.

Connections external to an exchange or subscribers' premises are always effected over a pair of wires to avoid trouble due to inductive interference. Any signalling between the terminal points of the external circuit must also, therefore, be performed over these wires. Internal signals, for convenience, can be passed over separate conductors.

Originally, earth return circuits were used; interference

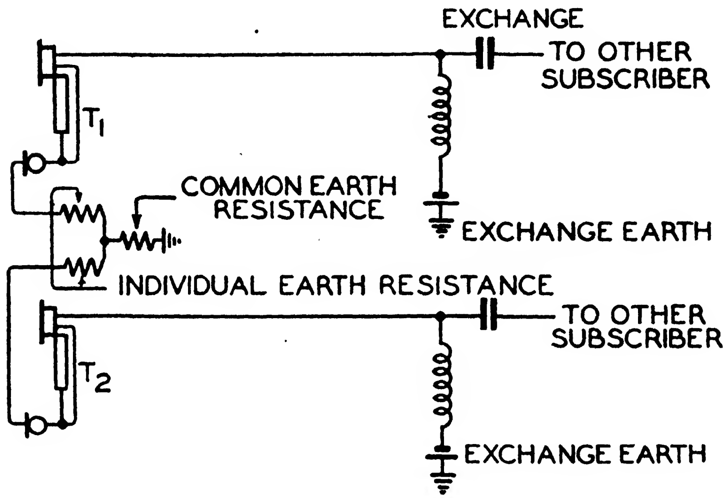


FIG. 10. EARTH RETURN CIRCUITS

between two such circuits will take place if they are in use simultaneously, owing to the common earth path.

Due to the resistance between the earth connections, small p.d.'s will be set up between T_1 earth and the exchange earth. These p.d.'s will be superimposed on the T_2 subscriber's circuit, and overhearing will result. The equivalent circuit is as shown in Fig. 10.

Only four types of signal are required between the subscriber and his exchange; they are—

(*a*) A calling signal to the exchange.

(*b*) A clearing signal to the exchange.

(*c*) A calling signal to the subscriber.

(*d*) An answering signal from the subscriber.

These signals are all effected over the two line conductors.

The standard conditions for the C.B. subscribers are—

State of Circuit	Condition at Subscriber's End	Condition at Exchange End
Normal	Disconnection to d.c.	Wet Loop* (Unbalanced)
Subscriber Calling	Dry Loop†	Wet Loop (Unbalanced)
Conversation	Dry Loop	Wet Loop (Balanced)
Subscriber Clearing	Disconnection to d.c.	Wet Loop (Balanced)
Exchange Calling Subscriber	Disconnection to d.c.	Low Frequency a.c. (17–25 cycles)
Subscriber Answering	Dry Loop	Wet Loop (Balanced)

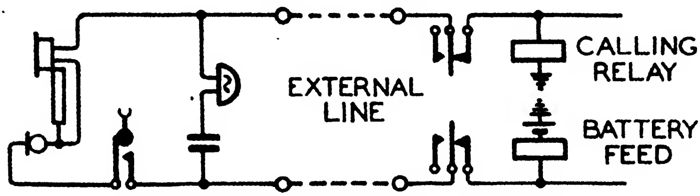


FIG. 11. SIMPLEST TELEPHONE CIRCUITS

The simplest circuits which will provide these facilities and at the same time allow for the transmission and reception of speech from the subscriber's instrument and the reception of calling signals at both exchange and subscriber's premises, are shown in Fig. 11.

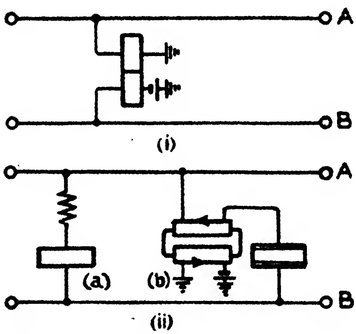


FIG. 12. 'WET' AND 'DRY' LOOPS
(1) 'Wet' loop. (2) 'Dry' loops.

For the subscribers' instruments the transmitter and receiver are shown in series, this being the simplest method of connection, and one which has been in the past used for short lines. It has disadvantages, however, and these, with the methods of overcoming them, will be discussed later. The individual components will first be analysed.

The Transmitter. The use of the carbon microphone as a transmitter in Telephony is practically universal.

* *Wet loop.* Earth and earthed battery, or loop battery, connected across a pair of conductors via relays or impedances.

† *Dry loop.* A circuit for direct current connected across two conductors, with no connection to battery or earth (Fig. 12).

The instrument consists essentially of a rigid base and a movable diaphragm, and attached to each is a carbon electrode, generally in the form of a polished disc. The diaphragm and base are clamped together so that the faces of the discs are opposite each other, and the space between them is almost filled with small carbon granules, suitable insulation keeping

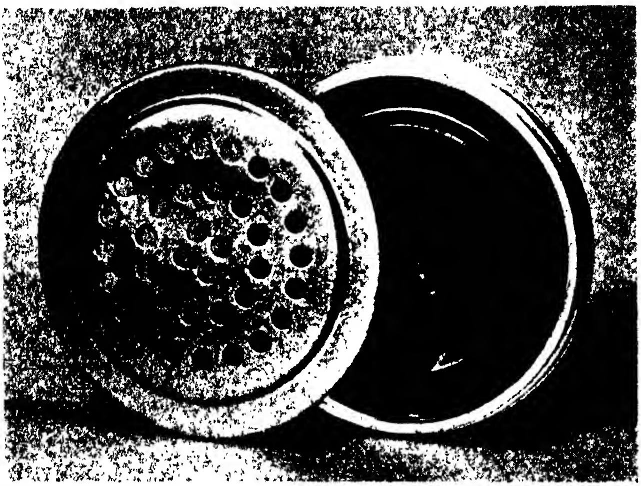


Fig. 13. Inset Transmitter
(*Siemens Bros. & Co. Ltd.*)

these latter from contact with any other conducting surface than the electrodes.

Two views of a modern 'inset' transmitter are shown in Figs. 13 and 14.

Normally the transmitter has a certain ohmic resistance (dependent on its type) of from 30 ohms to 80 ohms with d.c. flowing through it.

The diaphragm and electrode attached are set in motion by the sound waves impinging on the former when speech is being transmitted, and the resistance between the electrodes is thereby changed in value. This change in resistance is not entirely due to the minute changes in the distances between the movable and fixed electrodes, since the main resistance is also found to increase during transmission (Fig. 15), but is a characteristic phenomenon always observed when carbon is put under a

varying pressure, as in the carbon rheostat for example. The cyclic variation in the resistance, however, causes an alternating e.m.f. to appear at the terminals of the transmitter,

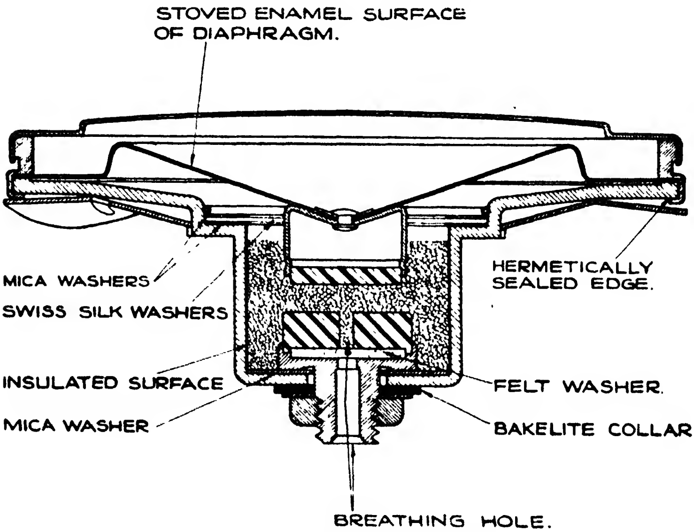


Fig. 14. Inset Transmitter
Cross-section.
(*Siemens Bros. & Co. Ltd.*)

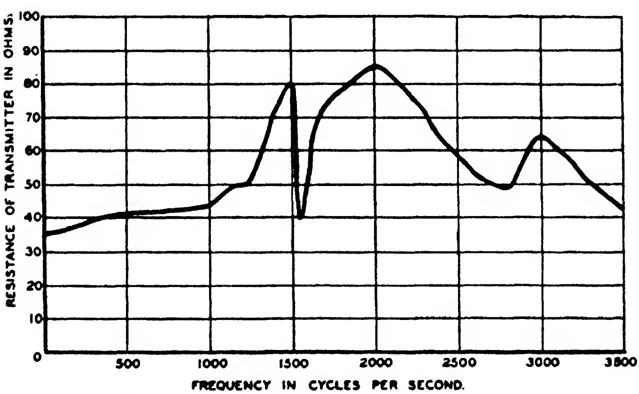


Fig. 15. Direct Current Resistance of Inset Transmitter

superimposed on the direct potential, which is the product of the line current and normal resistance. The nature of the alternating current thereby produced in the circuit can be roughly analysed as follows.

(For simplicity, a circuit containing non-inductive resistance only will be considered, but the necessary modifications for the more usual case where reactance is present can easily be made if desired.)

Let the normal resistance of the transmitter be r_0 ohms, and let this change, when the diaphragm is vibrating, from $r_0 - Mr_0$ to $r_0 + Mr_0$, where M is the modulation coefficient, determined by the efficiency of the instrument: e.g. if $M = 1$ (100 per cent efficiency) the resistance would change from $2r_0$ to zero every cycle, giving a mean value of r_0, as would be expected.

If the variation is sinusoidal, which is the normal state of affairs for undistorted tones of speech or music, the resistance at any instant will be $(r_0 + Mr_0 \sin \omega t)$ ohms, where $\omega/2\pi$ is the frequency of tone produced.

If the resistance of the rest of the circuit is R ohms, and the applied e.m.f. E volts, the normal current I_0 will be $E/(R + r_0)$ amps, and during speech conditions will be—

$$I_s = \frac{E}{R + r_0 + Mr_0 \sin \omega t}$$

$$= \frac{E}{(R + r_0)(1 + [Mr_0/(R + r_0)] \sin \omega t)}$$

$$= \frac{E}{(R + r_0)} \cdot \frac{1}{(1 + [Mr_0/(R + r_0)] \sin \omega t)}$$

Now, $\dfrac{1}{1 + [Mr_0/(R + r_0)] \sin \omega t}$, by division is

$$1 - \frac{Mr_0}{(R + r_0)} \sin \omega t + \frac{M^2 r_0^2}{(R + r_0)^2} \sin^2 \omega t - \frac{M^3 r_0^3}{(R + r_0)^3} \sin^3 \omega t + \text{etc.}$$

(compare $1/(1 + a)$, which, by division, $= 1 - a + a^2 - a^3 + a^4$, etc.). If $Mr_0/(R + r_0)$ is very much less than unity, higher powers than the second may be neglected, as they will be extremely small compared with $Mr_0/(R + r_0)$. In a telephone circuit, the following approximate values may be obtained—

$$M = 0{\cdot}1$$

$$R = 500 \text{ ohms}$$

$$r_0 = 50 \text{ ohms}$$

while $\sin \omega t$ varies from $+ 1$ to $- 1$. The value of $Mr_0/(R + r_0)$

is therefore 0·009, in this particular case, and the transmitted current is $I_s = (E/550)\,(1 - 0{\cdot}009 \sin \omega t + 0{\cdot}000081 \sin^2 \omega t -$, etc.)

The first term is the normal direct current, the second is the required alternating component at the desired frequency, but the third introduces harmonic distortion, since

$$\sin^2\omega t = (1 - \cos 2\,\omega t)/2$$

and a double frequency or second harmonic appears.

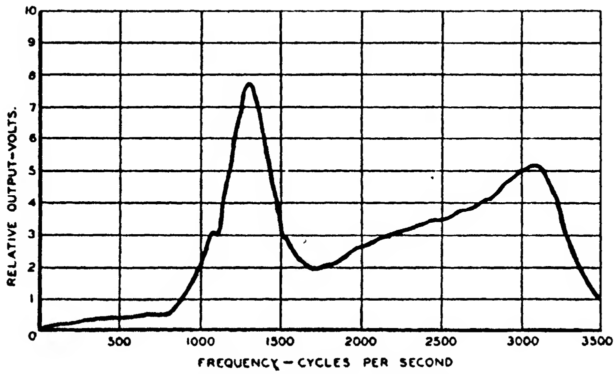


FIG. 16. FREQUENCY CHARACTERISTIC OF INSET TRANSMITTER IN STANDARD C.B. TELEPHONE CIRCUIT
(30 dynes per cm.²)

The following term would contain $3\omega t$ if expanded, but the numerical coefficient is negligible in ordinary cases.

Since the coefficient of the double frequency term contains M^2 in the numerator, it will be seen that sensitivity cannot be obtained without distortion in this type of transmitter.

Owing to mechanical resonances and other causes the response of the transmitter to any given air pressure at various frequencies is not constant, but varies somewhat as shown in Figs. 16 and 17.

The Receiver. The receivers used in telephony are of the electromagnetic moving iron type, in which the soft iron or stalloy diaphragm is clamped in front of soft iron pole pieces; forming a magnetic circuit the magnetic flux in which is varied by the passage of speech currents in coils wound on the poles. This variable flux is superimposed on a much larger steady flux which can be produced by direct current in the coils, or

more usually by a permanent magnet, and the resultant movements of the diaphragm convey the speech effects to the ear of the listener.

Consider a receiver with no permanent magnet, and let a constant current of I amperes flow round the circuit.

The diaphragm will be attracted by a force proportional to I^2 (since the flux is proportional to the current, and the pull is proportional to the square of the flux).

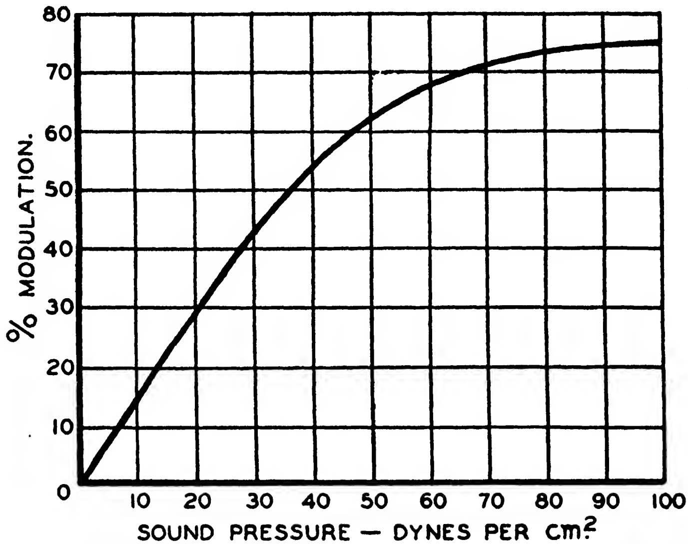


FIG. 17. PERCENTAGE MODULATION OF INSET TRANSMITTER RESISTANCE

Now, on the introduction of speech currents of the form $i \sin \omega t$, the current becomes—

$$I + i \sin \omega t$$

and the pull will now be proportional to—

$$(I + i \sin \omega t)^2$$

The change in pull, on which the movement of the diaphragm depends, will be the difference between these pulls,

or
$$(I^2 + i \sin \omega t)^2 - I^2$$
$$= I^2 + 2iI \sin \omega t + i^2 \sin^2 \omega t - \mathrm{I}^2$$
$$= 2iI \sin \omega t + i^2 \sin^2 \omega t$$
$$\doteq 2iI \sin \omega t + \tfrac{1}{2}i^2(1 - \cos 2\omega t)$$

The first term is the useful component, as it contains the correct frequency, and it will be seen to be dependent both on the strength of the polarizing current I and the speech current i.

The second term introduces distortion, as it contains the double frequency or *second harmonic* term $\cos 2\omega t$. It is customary to place the receiver in a local circuit where the direct current I does not flow through the coils. A steady flux is provided instead by a permanent magnet, which can be regarded as an equivalent of a certain fixed value of I.

The following advantages thereby result—

(*a*) The permanent magnetism is independent of the line resistance.

(*b*) The receiver can be worked on magneto or C.B.S. lines where no direct current is available.

(*c*) A standard adjustment for all receivers can be adopted.

With regard to (*a*) it will be noticed that with electromagnetic receivers, the magnetizing current will be weakest on long lines and strongest on short lines.

The sensitivity will therefore be less on the long lines and greatest on the short lines—the reverse of the desired conditions.

If the permanent magnetism (or polarizing current) is zero, it will be seen that the first term vanishes. The receiver responds only to the double frequency component, and the resultant speech is raised in pitch by one octave, while its amplitude is greatly diminished.

The impedance to alternating current of a standard bell receiver is 220 ohms at a phase angle of 44° measured at the mean speech frequency of 800 cycles per sec. With the receiver in a local circuit, the transformer can be designed to match this impedance with that of the line.

The receiver as used in the combination hand-set (or hand micro-telephone) has an impedance of 370 ohms and an angle of 59° at 800 cycles per sec. Its d.c. resistance is 80 ohms. The impedance at 800 cycles can be expressed as $160 + j155$ ohms for the bell receiver, and $190 + j320$ ohms for the h.m.t. instrument.

Electrical, Acoustical, and Motional Impedance. When speech currents flow in the receiver coils, the diaphragm is set in motion, and this motion is communicated to the adjacent air.

The movement of the diaphragm will be governed both by the pull of the poles and the resistance due to the imprisoned air between the diaphragm and the listener's ear, this latter effect giving rise to what is known as *acoustical* impedance.

Correct relation between this acoustical impedance and the

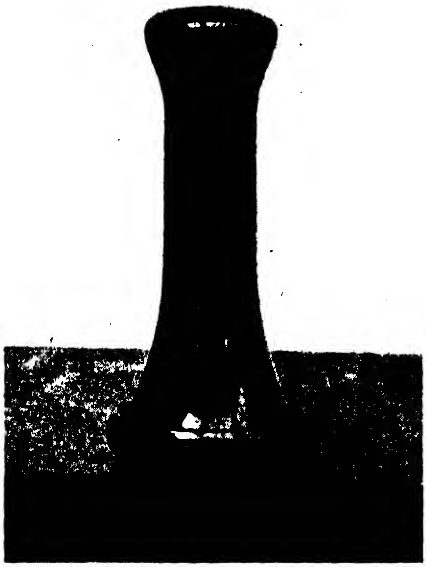


FIG. 18. BELL RECEIVER

normal electrical impedance will greatly improve the response of the receiver.

The electrical impedance is, however, modified when the diaphragm is set in motion, since the movement of the latter in front of the poles will cause variations in the flux, which in turn will set up e.m.f.'s in the magnet coils.

By Lenz's law, these e.m.f.'s will be in opposition to those producing the current variations and so will cause an apparent increase in the impedance of the receiver.

The magnitude and phase of these e.m.f.'s with respect to the applied voltage will vary with the frequency of the latter,

since the diaphragm has its own resonant frequency, at which its response is greatest.

The apparent change in impedance due to this effect is

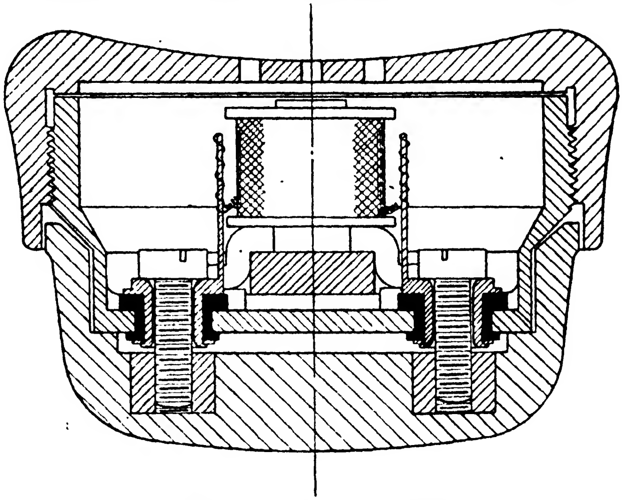


Fig. 19. Watch Receiver
Cross-section.

termed the *motional* impedance, which will vary with the frequency but will not be proportional to it.

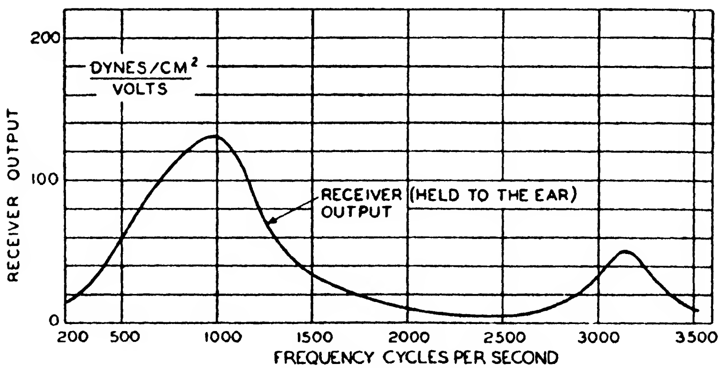


Fig. 20. Receiver Response Curve

The two standard types of receiver in current use are the *bell* receiver and the *watch* receiver. Both are shown in Figs. 18 and 19, and their method of operation should be apparent.

As in the case of the transmitter, the frequency response is not uniform with varying frequencies, and the response curve for a typical receiver is shown in Fig. 20.

The Induction Coil. Consider the simple circuit shown in

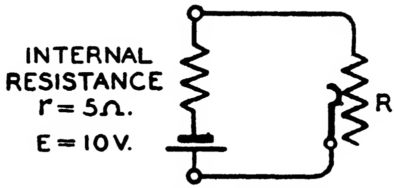


FIG. 21. CONDITIONS FOR MAXIMUM POWER

Fig. 21. When current flows from the battery, power is expended in the external resistance *R*, and also in the cell.

The useful power is that produced in *R*, and with the given

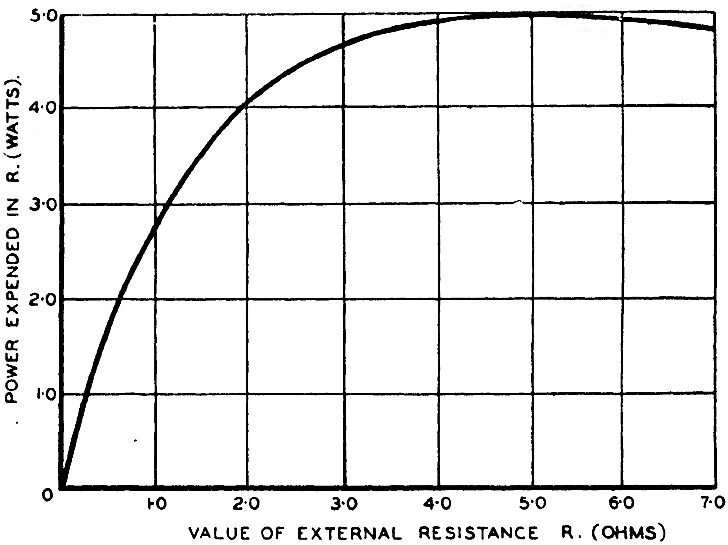


FIG. 22. POWER IN EXTERNAL CIRCUIT FOR VARIOUS VALUES OF *R*

source of supply, the power produced in *R* as this changes in value from 0 to 7 ohms is shown by the curve in Fig. 22. It will be noticed that the maximum power is obtained when the external resistance is equal to the internal resistance. The same relation holds whatever the value of e.m.f. or internal resistance,

and may be proved mathematically as follows. Let the e.m.f. of the supply be E volts, and its internal resistance r ohms. Then the current in an external circuit of R ohms resistance will be

$$I = E/(R + r) \text{ amperes}$$

The power produced outside the cell will be—

$$I^2R \text{ watts, or } W = I^2R$$

$$= \left(\frac{E}{R + r}\right)^2 . R$$

for this to be a maximum,

$$\frac{dW}{dR} = 0, \text{ or } \frac{(R + r)^2E^2 - E^2R \,.\, 2\,(R + r)}{(R + r)^4} = 0$$

Simplifying,

$$(R + r)^2 - 2R\,(R + r) = 0;$$

$$R + r - 2R = 0;$$

$$r - R = 0;$$

or

$$r = R$$

This relation is true for maximum power conditions whether the e.m.f. is an a.c. or d.c. source. In the alternating current case an allowance must be made for the phase angle of the external load, and in telephony it is frequently necessary to find some means of artificially raising or lowering the impedance of a piece of apparatus in order to obtain a greater response. It can be seen from the graph that, if it is not possible to obtain an exact balance of impedance, it is better to err on the high side rather than the low.

The impedance of a telephone line of normal proportions is approximately 600 ohms, at an angle of 45° leading. These values are due to its physical properties of resistance, inductance, and capacitance, which in turn are governed by the limitations of size and expense of the conductors and insulating media.

The matching of impedance is therefore effected at either end of the line, and it is customary to use a special type of transformer for this purpose. The power expended in a circuit is given by E^2/Z watts, and with no losses in the transformer,

$$E_p^2/Z_p = E_s^2/Z_s, \text{ or } (E_p/E_s)^2 = Z_p/Z_s.$$

Since $E_p/E_s = T_p/T_s$, it follows that the correct transformation ratio for a primary impedance of Z_p and a secondary

impedance Z_p is $\sqrt{(Z_p/Z_s)}$. This is only true if the transformer is 100 per cent efficient, and where an approximation to this efficiency is not obtained there will be some loss of power in the transformer.

Now, it is shown in Chapter XIV that the optimum impedance for a telephone instrument terminating a line of impedance $Z_1/\overline{\theta}$ is $Z_1/\underline{\theta}$, and under these conditions maximum power is received. As the majority of telephone lines have an impedance of 600 ohms or more, at a negative angle of 45°, it follows that the telephone instrument must have an impedance of approximately $600/\underline{45°}$ for best results.

The transmitter itself is practically non-inductive, and its resistance is only a fraction of the 600 ohms which it is desired to obtain. A step-up transformer is therefore used to increase the sending efficiency, and some means must be adopted to alter the phase angle from approximately zero (which would be its value with a non-inductive transmitter) to the desired value of 45°. This is conveniently effected by winding the transformer with an open core, thereby greatly increasing its effective impedance, since the coupling with the secondary winding is not nearly so perfect, and a large 'leakage' flux will be produced, which will give rise to an induced e.m.f. in opposition to that applied. The equivalent 'circuits' of transformers wound with open and closed cores, and with non-inductive loads across their secondary windings, are shown in Fig. 23.

R_p in each case is the apparent resistance of the primary winding, and is due largely to the presence of R_s in the secondary circuit. The relation between the values of R_p and R_s for a perfect transformer can be demonstrated as follows.

A generator of V volts (Fig. 24) is connected across the primary winding of T_p turns and impedance R_p. The secondary winding has T_s turns and the whole impedance of the closed circuit is R_s.

Then $I_p = V_p/R_p$ and $I_s = V_s/R_s = (V_p/R_s) \cdot (T_s/T_p)$, since $V_p/V_s = T_p/T_s$.

As the transformer is perfect, the power expended in the primary circuit is equal to that expended in the secondary, i.e.

$$I_pV_p = I_sV_s, \text{ or } (V_p/R_p) \cdot V_p = (V_s/R_s) \cdot V_s$$

Simplifying, $V_p^2 \,.\, R_s = V_s^2 R_p$

$V_p^2/V_s^2 = R_p/R_s$, but since $V_p/V_s = T_p/T_s$

$R_p/R_s = T_p^2/T_s^2$

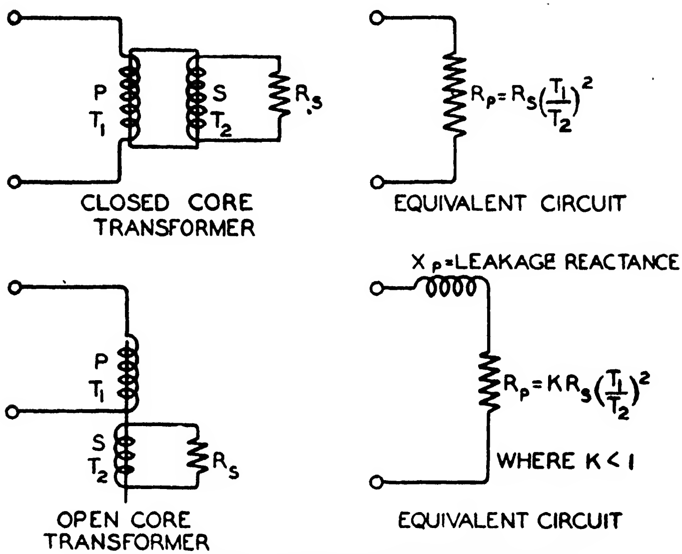


FIG. 23. EQUIVALENT TRANSFORMER CIRCUITS

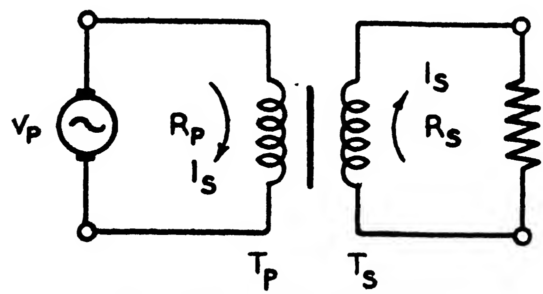


FIG. 24. PERFECT TRANSFORMER

This shows that $R_p/R_s = (T_p/T_s)^2$, and since $(T_p/T_s)^2$ is merely a numerical coefficient, the nature of the primary impedance depends upon that of the secondary. The transformer has been assumed perfect, which implies that all the lines of force produced by the primary cut all the secondary turns. The current induced in the secondary circuit will in

turn produce a flux, which, by Lenz's law, will be in the opposite direction. With a non-inductive load, the induced secondary current will be in phase with the induced secondary volts, and the flux will therefore be equal in value and opposite in direction to that produced by the primary winding. Thus the resultant flux is zero, and consequently the impedance offered by the transformer windings themselves is merely their d.c. resistance. Thus R_p can be entirely non-inductive if the transformer is perfect and the load a non-inductive resistance. If, as is always the case, the transformer is not perfect, some of the lines of force produced by the primary do not cut all of the secondary turns, and the resultant flux is not zero. This resultant, or *leakage* flux, cuts the primary turns and sets up in them a back e.m.f. which reduces the primary current, causing an apparent increase in primary impedance. It is this increase in impedance which is desired in the case of the telephone induction coil, and it is obtained by winding the primary and secondary on a straight iron core, the magnetic circuit being completed via the surrounding air. Further points in the design of the coil will be apparent when the telephone circuit as a whole has been considered.

Telephone Circuit (Fig. 25A). To meet the signalling requirements, the circuit (*a*) will suffice. The presence of the bell circuit across the lines will not interfere with the action of the transmitter or receiver, as the bell is of high impedance. It has at least one disadvantage, however, in that the direct current from the exchange, which is essential to the functioning of the transmitter, flows also through the receiver. The introduction of a transformer, as shown in (*b*), will overcome this disadvantage, and will also, by the choice of a suitable step-down ratio, match the high impedance of the line with the lower impedance of the receiver. The signalling and reception are now satisfactory, but the transmission of speech will suffer, due to the high impedance of the transformer primary placed in series. The alternating e.m.f. produced at the transmitter terminals will have to send alternating current through this impedance and the line in series, and it will be noted, from an examination of the equation for the speech currents produced by the transmitter, that the magnitude of these currents is inversely proportional to the total impedance in series. The

difficulty can be overcome by utilizing the transformer to step up the alternating e.m.f. before applying it to the line, and the simplest means of effecting this is as shown in (*c*). The generated e.m.f. is now applied to the local circuit as well as to the line, and as the local circuit is of lower impedance, it follows that the alternating current due to the transmitter will be comparatively high, and the voltage across the transformer

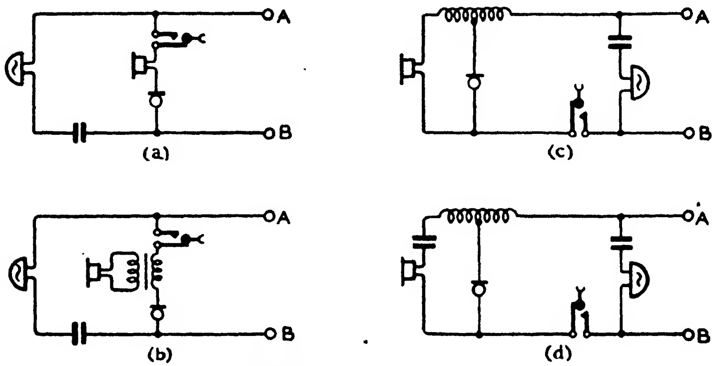


FIG. 25A. TELEPHONE CIRCUITS

(*a*) Simple series circuit.
(*b*) Receiver in local circuit.
(*c*) Transmitter connected via auto transformer.
(*d*) D.c. removed from receiver circuit.

winding in this circuit will be stepped up and transmitted to line via the line winding. There will also be in the line winding the alternating current due to the direct connection of the transmitter in series with the line coil; and by correct connection of the two coils, the e.m.f.'s produced directly and by induction can be made to assist each other. The two windings of the coil are then said to be connected as an *auto-transformer*, and the nominal step-up ratio is increased by unity; i.e. if the transformer had a step-down ratio of 2 : 1 from line to local circuit, the normal inverse step-up ratio of 1 : 2 from local circuit to line will be increased to 1 : (2 + 1) or 1 : 3, due to the addition of the original voltage in the line circuit. During reception of speech, however, the transmitter is not generating, and any voltage induced in the local circuit is by direct transformer action, except that the d.c. resistance of the transmitter will cause a small potential drop in phase with the line current, and consequently out of phase with the local

circuit current. This is a disadvantage, but it may be minimized by keeping the resistance of the transmitter low—the opposite requirement, as will be seen from the transmitter equations, from that of best transmission. A compromise is therefore necessary in the resistance of the transmitter and also in the ratio of the transformer, since the latter acts as an ordinary transformer during reception, and an auto-transformer during transmission. To take the example quoted above, the ratio would be 1 : 3 for transmission and 1 : 2 for reception. Correct impedance balance could not be obtained for both conditions, and in service telephones the ratio of the transformer (more usually termed *induction coil*) is chosen for best results on an average line—the ratio is intermediate between the optimum value for transmission and that for reception.

There are two difficulties still to be overcome if scheme (*c*) is adopted. Direct current again flows through the receiver, and besides affecting the strength of received speech, will also rob the transmitter of current and impair the sending efficiency. The insertion of a condenser in series with the receiver overcomes both objections, and is shown in (*d*).

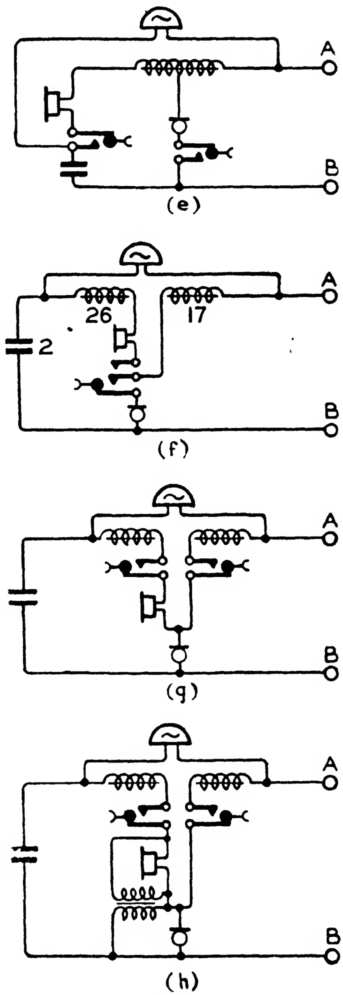


FIG. 25B. TELEPHONE CIRCUITS
(*e*) Components re-arranged.
(*f*) P.O. Telephone No. 150 and Bellset No. 1.
(*g*) P.O. Telephone No. 162.
(*h*) P.O. Telephone No. 162 with Anti-side-tone Transformer.

As a final simplification, the components are rearranged as shown in (*e*), and it will be noted that the bell in series with the condenser has been incorporated

in the circuit so as to fulfil both functions. This is the modern C.B. circuit in its simplest form (Fig. 25B)..

The gravity switch contacts, when normal, must disconnect both the transmitter and receiver, and permit other instruments to be connected in parallel, either directly or by means of plugs and sockets. A common bell will suffice for several instruments, only one of which must be in use at a given time.

Earlier types of telephone instrument, notably the pedestal type (P.O. No. 150), had only three contacts in the switchhook, arranged as shown in (*f*) (Fig. 25B), whereas a later circuit (P.O. No. 162) had four (*g*). In either circuit, however, the contact spring connected to the receiver must make contact after the others, and so prevent a loud 'click' being heard on completion of the d.c. circuit. This feature is obtained automatically by the mechanical construction of the contact assembly.

Modern Telephone Circuits. The circuit shown in (*f*) (Fig. 25B) is in use in considerable numbers. Its greatest disadvantage is the production of 'side tone' in the receiver when the transmitter is spoken into. It will be noted that the whole of the current in the local circuit produced by the transmitter e.m.f. passes through the receiver, and the subscriber therefore hears his own voice. On short lines, the discomfort produced thereby is serious, and leads to a natural diminution in the intensity of sound pressure produced by the speaker, so as to avoid the worst effects of 'side-tone.' To overcome this difficulty the *anti-side-tone transformer* was introduced. This consists of a small transformer located in the base of the telephone, with one winding across the transmitter and the other across the receiver (*h*).

The direction of winding is such that the current induced into the receiver by transformer action from the transmitter is in opposite phase to that produced by the induction coil. The intensity of the side-tone is reduced by this means, but the reception of incoming speech naturally suffers, since one winding of the transformer is virtually short-circuited by the transmitter. This anti-side-tone arrangement is effective on C.B. and automatic subscribers' instruments, but is being superseded by an improved circuit which obviates the necessity for a separate transformer.

Anti-side-tone Circuit. The latest arrangement is shown in outline in Fig. 26. The receiver has been removed to a local circuit, and the transmitter is tapped across the primary winding of the induction coil at a point such that the impedances of the line and local circuits are more or less balanced, the balance being assisted by the introduction of a series resistance in the local circuit. The alternating current produced by the transmitter divides approximately evenly into the two circuits, and with good balance between line and local circuit, no current is produced in the receiver due to the action of the transmitter. When speech is being received, the transmitter merely shunts a portion of the line winding, in all parts of which the current is now in the same direction. The receiver responds to the currents induced from the line winding, with but small loss occurring.

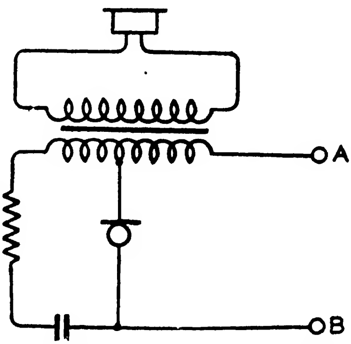


FIG. 26. ANTI-SIDE-TONE CIRCUIT —IDEAL ARRANGEMENT

The circuit is only suitable, however, for one particular type of line, and the presence of the condenser in the local circuit helps to produce the capacitive reactance usually found in a subscriber's line.

A further modification, rendering the circuit more suitable for general conditions, is shown in Fig. 27. Here an additional resistance is inserted in series with the local transmitter circuit, and the voltage drop across this resistance is injected into the receiver circuit. This voltage will be out of phase with that produced by any transformer action, and the resistance value is chosen to produce the best results with the average line.

In the practical circuit, provision must be made for simplifying the connections to the hand-set, and for convenient attachment of a dial for automatic working, or additional telephones in parallel. The actual connections are shown in Fig. 28, and it will be noted that the series resistance of 85 ohms has been connected between the two parts of the line winding, but the theory of its operation remains unchanged. The 30-ohm

resistance in series with the end of the coil serves only as part of the spark quench circuit in automatic working, and has no influence on the transmission. The resistance and number of

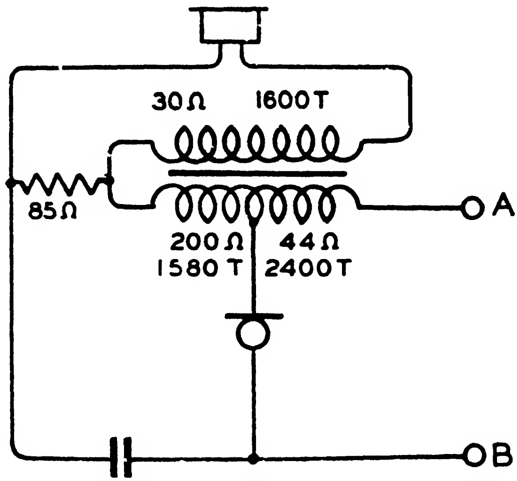


FIG. 27. ANTI-SIDE-TONE CIRCUIT—PRACTICAL EQUIVALENT

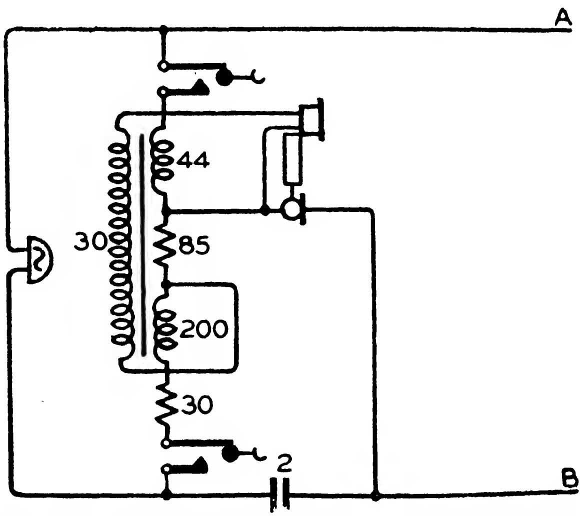


FIG. 28. COMMON BATTERY ANTI-SIDE-TONE TELEPHONE

turns in each winding is indicated, the high resistance in the local circuit being obtained by winding that portion of the coil with fine gauge wire. It will be observed that the scheme

adopted in connecting the various components results in the minimum number of cord connections to the hand-set, and to the dial, when fitted.

Automatic Telephone. The anti-side-tone telephone circuit for automatic working is the same as for common battery use, except for the addition of the dial (Fig. 29). It will be noted that the impulse springs make and break the loop circuit, whilst

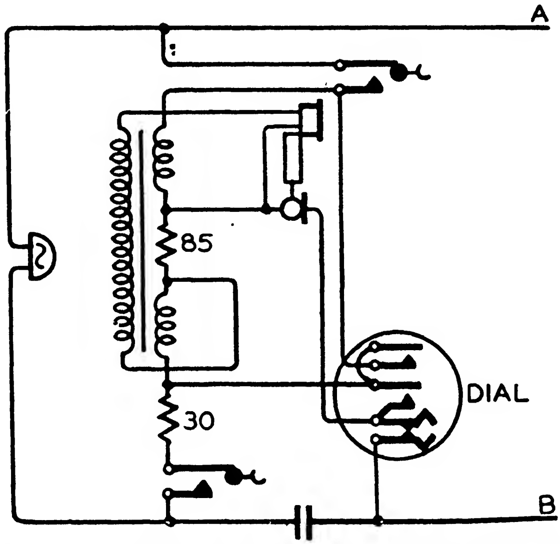


FIG. 29. AUTOMATIC SYSTEM—ANTI-SIDE-TONE TELEPHONE

the condenser serves for spark quench purposes, to prevent the production of high induced voltages during dialling, which would otherwise damage the insulation and distort the impulse wave form.

The bell is prevented from tinkling during dialling by being short-circuited at the 'off normal' contacts of the dial, which also serve to prevent any flow of current in the receiver, otherwise annoying 'clicks' would be produced. The 30-ohm resistance serves to prevent the discharge current of the condenser from reaching a value high enough to cause damage to the impulse springs on the 'make' of the latter. The value is limited to 30 ohms, since if a higher resistance were employed, bell-tinkling would occur during impulsing.

Local Battery Telephones (Manual). On long lines, where the

resistance of the line conductors results in the diminution of the transmitter feeding current to a value below that necessary for satisfactory transmission, the transmitter is removed from the line, and placed in a separate circuit with a local battery of from 3 to 6 volts, a three-winding induction coil being employed to give the correct impedance relationships between line and local circuits.

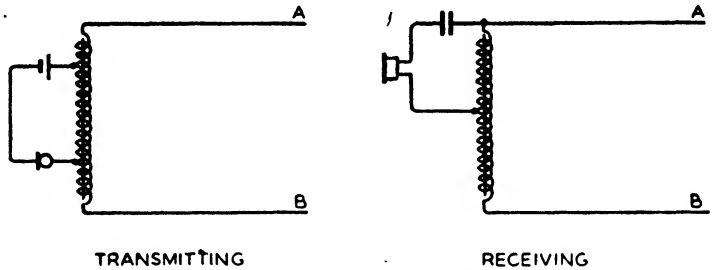


FIG. 30. LOCAL BATTERY TELEPHONE
Outline circuits.

The schematic arrangement is shown in Fig. 30, and it will be noted that both the transmitter and receiver are connected on an auto-transformer basis. The transformer tapping points are chosen to give the best overall results, and three separate coils on the one core are used. Contacts of the gravity switch disconnect the line and local circuit when the hand-set is replaced, leaving the bell and condenser across the line.

The side-tone produced by this circuit (Fig. 31) is not so severe as in the original C.B. instrument, since the currents produced in the transmitter and line coils are in opposite phase during sending, while during reception the transmitter coil is practically short-circuited, and the receiver is fed from the secondary of a step-down auto-transformer. The condenser is again of value in matching the impedance of the receiver circuit with that of the line.

Local Battery Telephones (Automatic). The telephone used for long lines connected to automatic exchanges is shown in Fig. 32, and will be seen to be similar to that used for manual working plus the dial. The impulsing springs are inserted in series with the d.c. loop circuit, and one of the pairs of 'off normal' springs are used to short-circuit the receiver. During impulsing, the bell is shunted by the 33-ohm winding of the

induction coil, and the 17-ohm winding, in conjunction with the 2 μF. condenser, acts as a spark quench on the dial contacts.

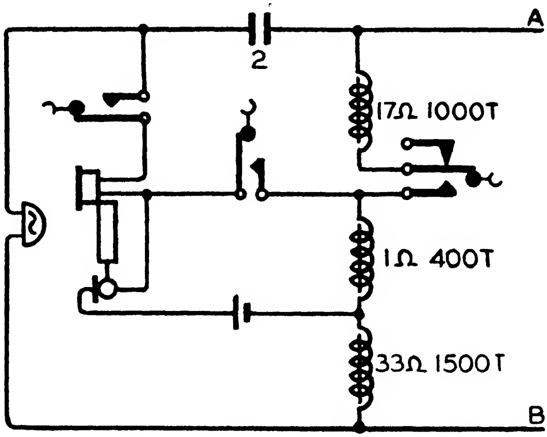


Fig. 31. Local Battery Telephone Set
Manual.

Telephones in Parallel. C.B. or local battery telephones may be connected in parallel, so that access to the exchange may be obtained from two or more different points. The diagram of

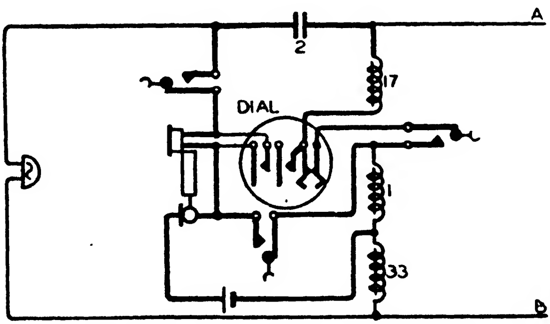


Fig. 32. Local Battery Telephone
Automatic.

connections (Fig. 33) is self-explanatory, the only point of importance being that the bells at the extension telephones are in series with that in the main instrument, and may be cut out as desired with a switch. Intercommunication between instruments is not possible, but if a call is received at any

station, arrangements can be made for any of the other stations to be called in on the line by means of a d.c. trembler bell and press button scheme, current for this purpose being drawn from the exchange line.

Another arrangement provides for the termination of the exchange line on a series of sockets, the instrument being

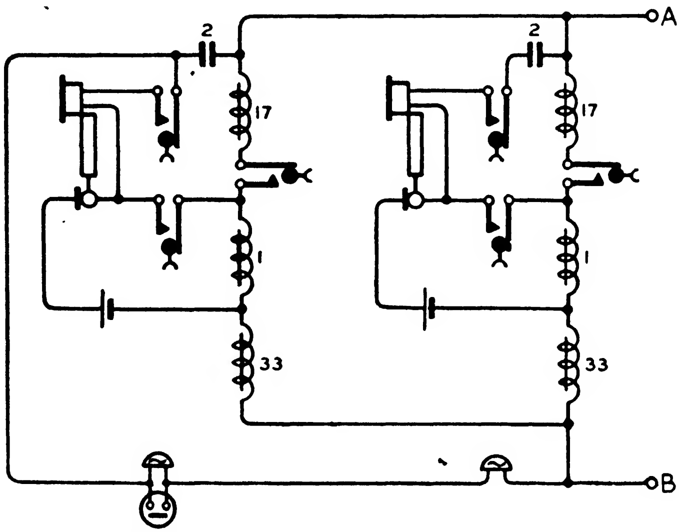


FIG. 33. LOCAL BATTERY EXTENSION WORKING

provided with a plug on a flexible cord, so that it may be plugged in at any of several points on the circuit. The bell is connected via contacts on the socket at each termination, and remains in circuit even when no instruments are plugged in.

Telephones with Intercommunication. With this system, the exchange line terminates on a bell-set (P.O. No. 20) provided with a switch, which has four positions. In the normal position, MAIN TO EXCHANGE, the main telephone terminates the exchange line, and the extension line is connected to a bell in the bell-set (Fig. 34).

With the switch turned to MAIN TO EXTENSION, the main and extension telephones are connected together, and generators are provided for ringing between them. Current for speaking purposes is supplied by a small battery of primary

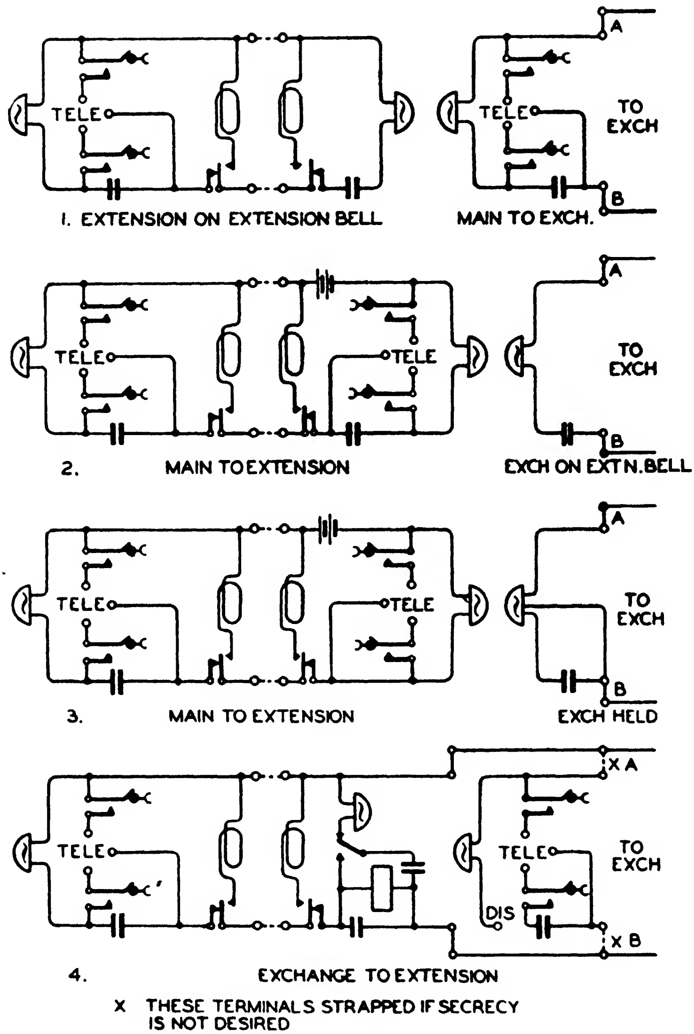


FIG. 34. COMMON BATTERY SYSTEM

Extension working with intercommunication.

cells. The exchange line is terminated by the bell and condenser in the bell-set.

The third position, MAIN TO EXTENSION, EXCHANGE HELD, is the same as above, except that a holding coil consisting of one-half of the bell windings is placed across the exchange line. This permits an exchange call to be answered, and then held while the extension line is rung for inquiry or other purposes.

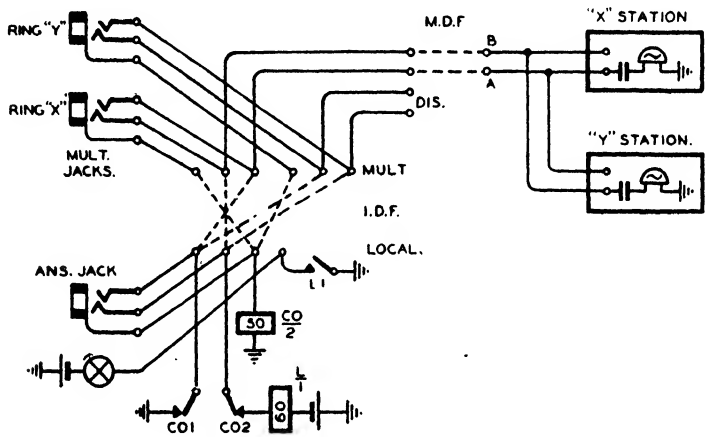


FIG. 35. C.B. EXCHANGE
Two-party line circuit.

The last position, EXTENSION TO EXCHANGE, extends the exchange line right through to the extension, leaving a bell and condenser across the line at the main bell-set. At this point a relay indicator is also inserted in series with the line, so as to provide an indication as to whether or not the extension instrument is in use. The indicator shows a distinctive signal when current is flowing in its coil.

Two-party Lines. On manual exchanges, two subscribers' stations may be connected to one exchange line, and by connecting the bell circuits to earth instead of across the lines, the operator can discriminate between the subscribers when calling them from the exchange. Each subscriber has a separate multiple appearance, one set of jacks having the tip and ring connections reversed at the I.D.F. The X-station is rung over the A-line and the Y-station over the B-line. There is no secrecy on calls from either subscriber (Fig. 35).

Prepayment Coin Box Circuit—Automatic System. The circuit is shown in Fig. 36. The values of resistance in the induction coil circuit are different from those used in the ordinary telephone circuit, but the theory of operation is the same. The action of the coin box telephone is as follows—

Caller removes microtelephone, and inserts two pennies.

First penny operates spring-set No. 1.

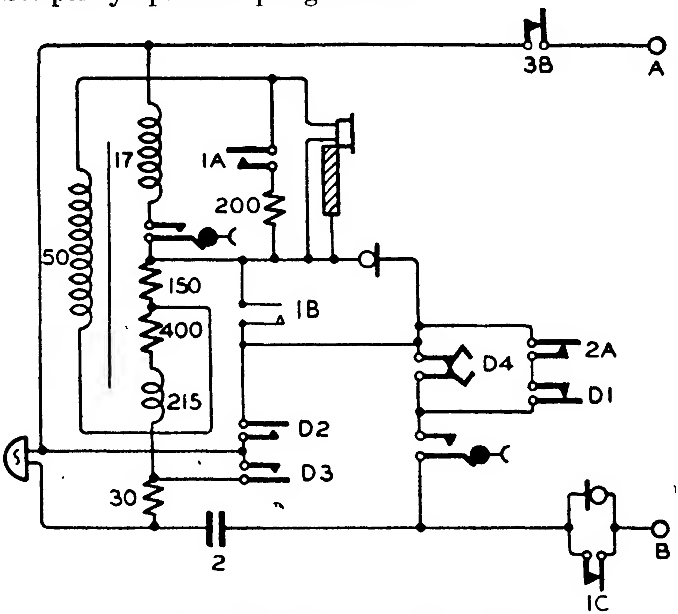


Fig. 36. Prepayment Coin Box Circuit
Automatic.

1*A* places 200-ohm shunt on receiver, and prevents its use as a transmitter.

1*B* short-circuits the transmitter.

1*C* removes short circuit from coin box transmitter, which transmits distinctive tones to the operator, when '0' has been dialled and coins are inserted for a trunk call.

Second penny operates spring-set No. 2, the additional weight causing a balanced lever to operate.

2*A* removes short circuit from dial, and caller proceeds to dial required number.

The off-normal springs *D*2 and *D*3 of the dial function as in the ordinary subscriber's instrument.

*D*1 does not operate except when '0' is dialled.

When the distant subscriber answers, the caller cannot speak until Button 'A' is depressed.

This button returns spring-sets 1 and 2 to normal, and allows call to proceed as on a standard circuit, the coins being deposited in the cash box.

If Busy tone is received, or the call is ineffective for any other reason, Button 'B' is depressed. This also restores spring-sets 1 and 2 to normal, but in addition discharges the suspended coins into the chute, and operates spring-set 3, which is maintained operated for approximately 7 sec. by means of a clockwork escapement. This interval is sufficient to allow an adequate clearing signal to be given, and prevents the coin box user re-calling after pressing Button 'B,' and without inserting further coins. 3*A* is spare and 3*B* allows the exchange apparatus to restore to normal. Automatic coin box instruments are connected to normal calling equipments at the automatic exchange, but the switches serving them are in a 'Barred Trunk' group. If the coin box user dials codes of exchanges beyond the unit fee area, N.U. tone is returned from the switch levels in this group, and, if '0' is dialled, a circuit in a separate group is taken into use, and a distinctive lamp cap marking warns the operator that a fee must be collected.

To obtain the operator, '0' is dialled without inserting any coins. The *D*1 spring-set on the dial operates under this condition, and removes the short circuit from the impulse springs.

The caller is requested to insert coins to the correct amount, and the different denominations of coin actuate different sounding gongs placed near the special coin box transmitter, spring-set 1 being operated by the first coin as before. The coins are passed into discriminating chutes, which test them for size, and cause them to strike the appropriate gong. The note given out by the gong is communicated to the operator via the coin box transmitter, which is protected in such a way that it cannot be utilized for ordinary transmission.

Prepayment Coin Box—Manual. The instrument circuit is shown in Fig. 37, and the line and cord circuit in Fig. 38.

OPERATION. The caller removes the microtelephone, and inserts two pennies.

The first penny operates spring-set 1.
1A shunts the receiver.
1B prepares the calling circuit to the exchange.

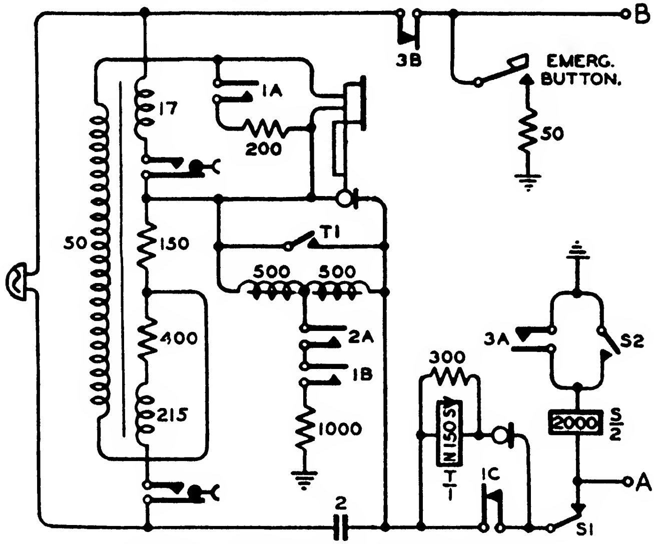


Fig. 37. Prepayment Coin Box Circuit
Manual.

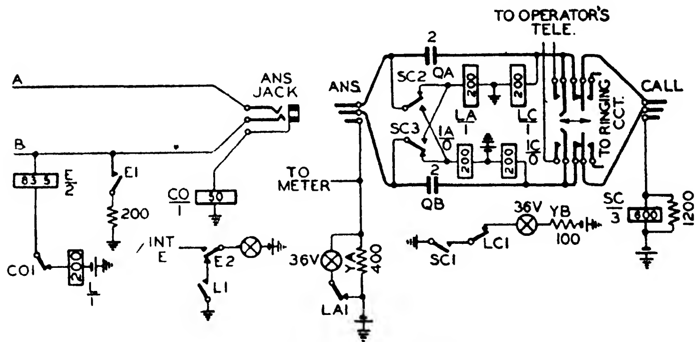


Fig. 38. C.B. System
Prepayment coin box line equipment and coin box cord circuit.

1C removes the short circuit from the polarized relay T and the coin box transmitter.

The second penny operates spring-set 2.

2A completes the calling circuit by applying earth to both lines via the tapped impedance coil.

Relay L operates at the exchange, causing the calling lamp to glow. E does not operate in series with L to the high resistance earth.

The operator inserts the answering plug of a coin box cord circuit and CO operates from the sleeve. CO disconnects L and extinguishes the calling lamp. Battery is sent out on the B-line, and the polarized relay T does not operate, but LA in the cord circuit does, being unaffected by the high resistance earth from the telephone circuit.

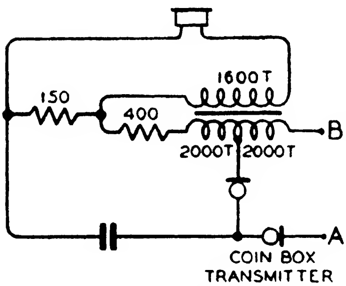


FIG. 39. COIN BOX TELEPHONE —OUTLINE CIRCUIT

The operator ascertains the caller's requirements, and completes the call with the calling plug.

The operation of SC to earth on the bush of the jack reverses the polarity of the wet loop on the answering side, and relay T in the telephone set operates, short-circuiting the transmitter.

When the caller hears the distant party on the line, Button 'A' is depressed, discharging the coins into the cash box, and restoring spring-sets 1 and 2.

1A removes the shunt from the receiver.

1B and 2A remove the calling earth.

1C releases T and cuts out the coin box transmitter. If more coins are required, the operator instructs the caller to insert these prior to pressing Button 'A,' and the gongs signal to the A-operator, by means of the coin box transmitter, the value of the coins that have been inserted.

If for any reason the call is ineffective, the caller depresses 'B,' which allows him to recover the coins, and also restores spring-sets 1 and 2, and operates spring-set 3 for seven seconds.

3A completes an operating circuit for relay S which holds via $S2$. $S1$ disconnects the A-line.

3B disconnects the B-line, and causes the cord circuit supervisory lamp to glow.

The operator clears the connection, thereby causing S to restore, and the circuit is again normal.

Emergency Calls. The exchange may be signalled without the

insertion of two pennies, if the 'Emergency Button' is pressed. A low resistance earth is thereby connected to the B-line, and both relays *E* and *L* operate at the exchange. A distinctive flashing signal is given to the operator, as the calling lamp is connected to the intermittent earth. Relay *E* locks over its own contact until the call is answered.

Telephone Circuit. Fig. 39 shows the outline circuit for transmission of speech and tones. The different values of resistance, as compared with the standard subscribers' circuit, are employed to suit the impedance of the average line used on coin box calls.

CHAPTER III

PRIVATE BRANCH EXCHANGES

WHERE a subscriber has more than one extension telephone, and full intercommunication between extensions and the exchange line or lines is desired, a switchboard is provided at the subscriber's premises, and the complete installation is described as a *Private Branch Exchange* (P.B.X.).

The switchboards used on common battery manual and automatic systems are of two types, the larger being equipped with cord circuits and jacks as in an exchange switchboard and the smaller with sufficient keys to effect the maximum number of switching combinations possible. This latter type, termed *cordless*, is suitable for installations consisting of from one to three exchange lines, and from two to ten extensions.

Cordless Switchboard. In the Post Office service these boards are known as "Cordless No. $\frac{1+3}{4}$, No. $\frac{2+4}{6}$, and No. $\frac{3+7}{12}$," the first figure giving the number of exchange lines, the next figures giving the local or extension lines, and the figures below the line denoting the ultimate capacity; the largest of the boards being capable of being extended from ten to twelve lines. The latter board is also provided with three rows of connecting keys. The calling indicators for the exchange lines are 1 000-ohm (as shown on the left of the second row), and those for the extensions are 500-ohm 'eyeball' signals shown in the same row. The latter signals also serve as clearing signals for the same line, and are all provided with alarm contacts to give an audible as well as visual signal.

Two rows of keys are used for making the connections, the upper positions and the lower positions of the upper row of keys being used for this purpose, whilst the lower position of the lower row is used for ringing by generator in the case of the extensions, and for holding, by connecting a 750-ohm coil across the loop, for the exchange lines.

A view of the $\frac{1+3}{4}$ cordless board is given in Fig. 40A.

The connecting keys for each line, all coloured white, are

directly below the signal or indicator for each line so that no mistakes should be made. Any keys in the same horizontal row turned to the same relative position, top or bottom, will cause the lines connected to those keys to be joined together; thus on the board shown there is provision for two pairs of lines to

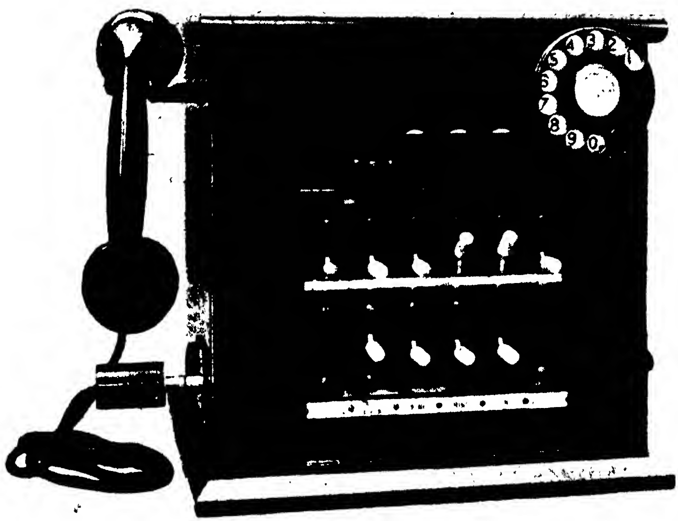


FIG. 40A. CORDLESS SWITCHBOARD

be connected, via the upper and lower positions of the top row of keys.

The right-hand keys in each row of switching keys are used for answering purposes by the switchboard operator, the call being made at the extension instrument by lifting the receiver.

The clearing signal is a positive one, and always appears vertically above the connecting key on which the call is set up.

The connections of one exchange line and one extension line of this board are given in Fig. 40B. It will be seen that the supervisory relay with a non-inductive shunt is inserted in series in each connecting circuit. This relay operates the supervisory signal. When the connecting keys are in their normal central position the extension line calling signal is

connected in circuit with the extension line by means of additional contacts on the connecting keys, its connections are changed when an associated key is thrown, and its circuit is

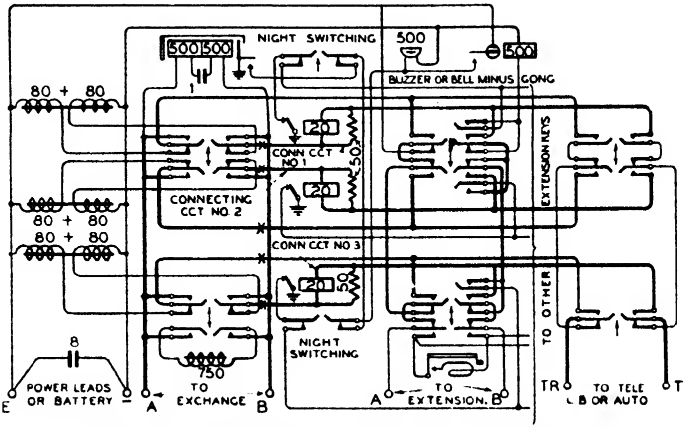


FIG. 40B. CONNECTIONS OF CORDLESS SWITCHBOARD

then completed via the contacts of the 20-ohm supervisory relay in the connecting circuit. When, therefore, at the conclusion of a call, the extension station hangs up, the supervisory

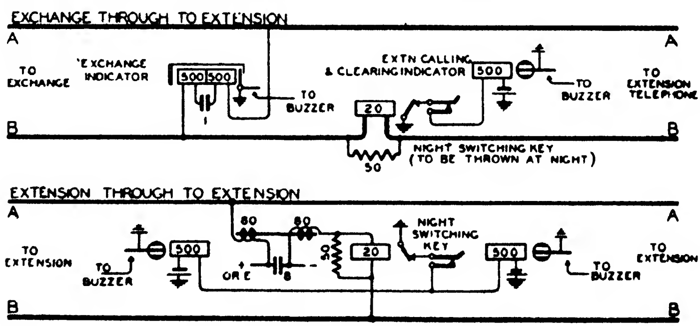


FIG. 41. EXPLANATORY CIRCUITS
Cordless switchboard.

relays falls back and the extension line signal is operated. A night extension key in each connecting circuit, shown on extreme left of Fig. 40A provides for cutting out the supervisory signals when an extension line is put through permanently to the exchange for night service. Through circuit connections are shown in Fig. 41.

It should be noted that on extension to extension calls, neither eyeball indicator is actuated until both parties have cleared, when both indicators operate simultaneously.

Through clearing is given to the main exchange on extension calls, and for automatic exchange areas, the normal dial is added to the operator's circuit, and also to any extension telephone which may be switched through at night.

Double Cord Boards. The larger P.B.X. installations are served by switchboards which stand on the floor, and which resemble ordinary exchange equipment in appearance and method of operation. There are four main types, as follows.

(1) A 25-line board, with indicator signals giving 'positive' supervision.

(2) A 65-line board, with an ultimate capacity for 180 lines. This board has 'negative' supervisory signals of the indicator type in the cord circuits.

(3) A multiple switchboard capable of extension to meet all but the very greatest requirements, but with indicator signals and negative supervision in the cord circuits.

(4) A multiple switchboard of the same type as is used in common battery exchanges. Lamp signalling and 'positive' supervision are provided.

Types (1), (2), and (3) give through clearing facilities on extension to exchange calls, as on cordless boards, and it is not therefore possible for the extension user to 'call in' the P.B.X. operator by 'flashing' on the gravity switch, without also giving a clear to the exchange—or releasing the connection if the call is outgoing to automatic switches.

The advantage of being able to control the main exchange supervisory signals, and therefore the timing equipment, from the extension instruments, outweighs the loss of the 'calling in' facility, which is only given by switchboards of type (4). At these installations the P.B.X. operators have control of the exchange lines, and are assisted by full supervisory facilities on answering and calling cords.

Night Switching Keys. Key contacts designated *N* will be noted in the various diagrams, and these indicate the points where connections are broken to enable certain extensions to be plugged through to exchange lines when the P.B.X. switchboard is not staffed.

In general, supervisory and alarm circuits are disconnected, so that there is no waste of battery power, whilst full signalling facilities are afforded between the extension and the exchange.

25-Line Switchboard (Fig. 42). The exchange lines are terminated on jacks, the inner springs of which are connected to the calling indicator, in series with a condenser. A.c. ringing from the exchange actuates the indicator, which is cut out of circuit on the insertion of a plug in the jack. The bush of the jack is earthed via contacts of the night switching key as shown in Fig. 43.

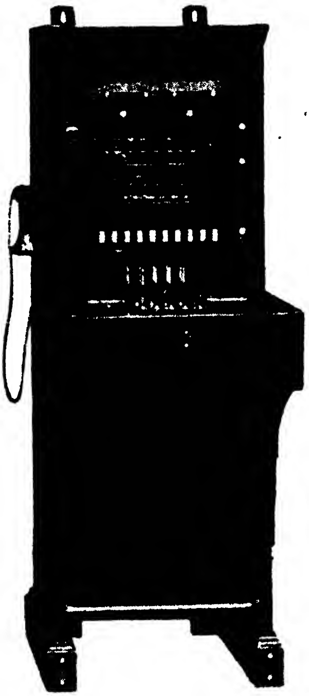


FIG. 42. 25-LINE SWITCHBOARD
(*General Electric Co. Ltd.*)

The extension line jacks are connected differently. There is a 20-ohm relay (shunted with a non-inductive resistance) in series with the ring conductor, and this relay, which is operated as long as current is flowing in the extension loop, controls the positive supervisory signal.

A 'doll's eye' indicator, connected via the jack springs and night key contacts, operates as a calling signal when the extension comes on the line, and functions as a clearing signal when a plug has been inserted in the jack. A contact on the indicator is used to actuate the night alarm, which is also commoned to contacts of the exchange line indicators.

The cord circuit is provided with two keys—'SPEAK' and 'DIAL CALL-RING ANS + RING CALL.' The former fulfils the the normal function of permitting the operator to speak on either side, whilst the latter enables the operator to ring on the answering or calling cord, or cut off the extension loop across the answering cord when dialling out on the exchange line.

Normally, on extension to extension calls, battery and earth for speaking and signalling purposes is fed to the ring and tip of the cord circuits via impedance coils. On calls extended to the exchange, a relay operates to earth via the sleeve when the plug is inserted into the exchange line jack, and contacts of

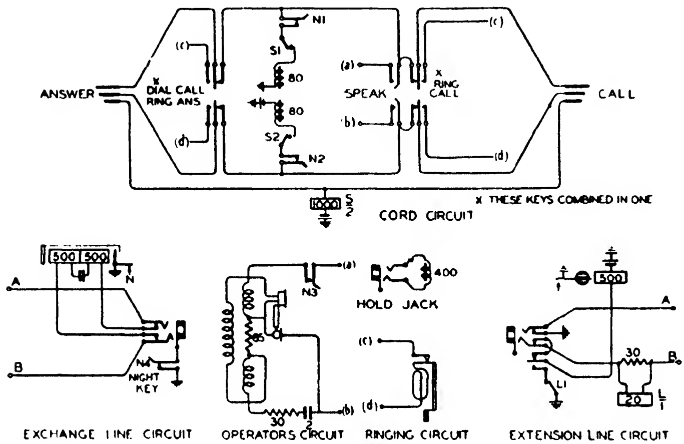


FIG. 43. 25-LINE P.B.X. SWITCHBOARD CIRCUIT

this relay cut off the impedance coils, and the line current flows only from the exchange battery.

For holding exchange calls under other conditions, e.g. whilst inquiries are being made on other lines, a hold jack is provided, which also serves for cord test purposes.

The operator's circuit consists of a standard telephone set without the bell, and is fitted with a dial in automatic areas.

Any extension may be put through to the exchange under night service conditions, contacts of the night switching key preventing the operation of any relays or indicators.

The circuit connections are shown in Fig. 43.

65-Line Switchboard (Fig. 44). The exchange line connections are the same as in the 25-line board, except that there is no night key contact in series with the bush of the jack.

The extensions are terminated on the outer springs of jacks, the inners of which are connected to earth and battery via the coil of a 'doll's-eye' indicator, which is used only as a calling

signal. Fig. 45 shows the connections for the line and cord circuits.

The latter are provided with flap indicators which give a 'negative' clear, i.e. they are actuated as long as the circuit

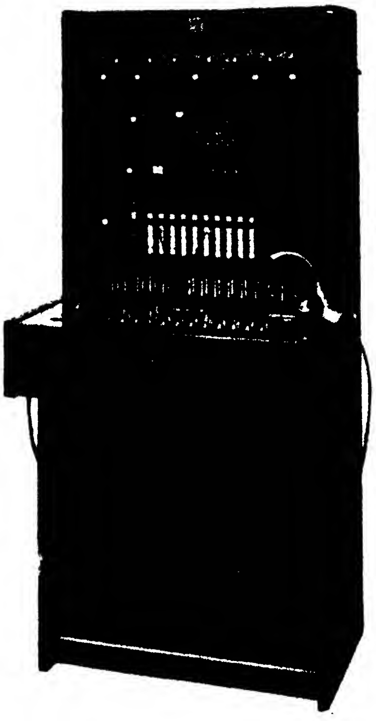


FIG. 44. 65-LINE SWITCHBOARD
(*General Electric Co. Ltd.*)

is occupied, and restore when the circuit is cleared. By this means individual supervisory signals can be given on answering and calling cords without drawing any additional current from the battery. The two cord circuit indicators are bridged by a 2 μF. condenser to minimize transmission losses, and on extension to extension calls the battery and earth are fed through the balanced windings of an impedance coil. This bridging impedance is cut out when an extension is extended

to the exchange by operation of the relay in series with the sleeve conductors. Both supervisory indicators are then in series with the exchange battery, and the extension loop controls the call.

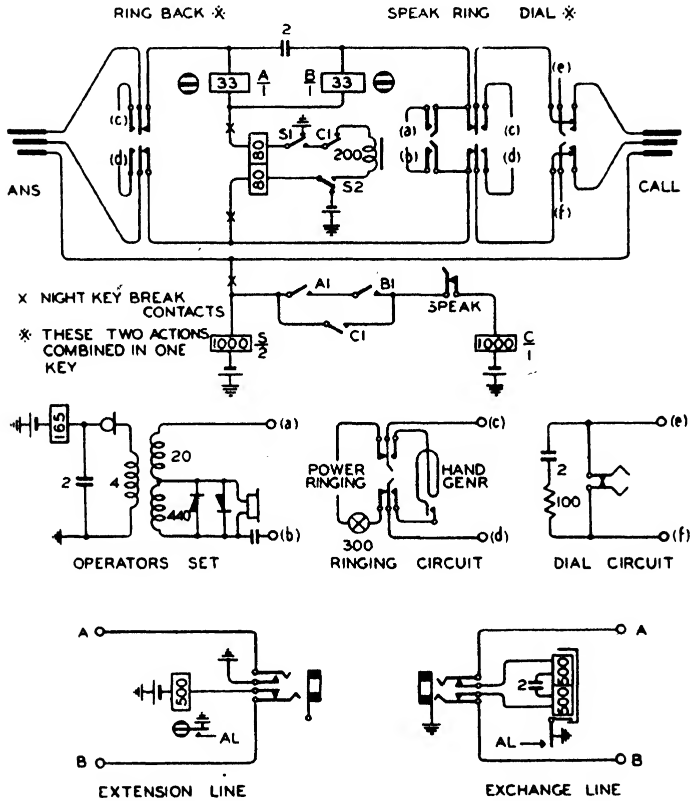


FIG. 45. 65-LINE P.B.X.—LINE AND CORD CIRCUITS

The operator's circuit is adapted for use with breastplate transmitter and headgear receiver, or with a hand-set, as desired. The circuit is similar to that used in main exchanges. Owing to the connection of a condenser in series with the secondary winding, it is necessary to provide a d.c. shunt on the cord circuit when answering an exchange call. This is effected by the additional 200-ohm impedance connected between the inner ends of the 80-ohm + 80-ohm bridging

impedance, by the operation of the sleeve relay in each cord circuit.

Normally, on extension to exchange calls, this 200-ohm impedance is disconnected by a contact of relay *C*, which operates (via contacts *A*1 and *B*1) as soon as the extension comes on the line, but releases when the speaking key is thrown.

When the operator restores the key, relay *C* is reoperated via *A*1 and *B*1, and holds over its own contact until the plug is withdrawn from the exchange line, thus preventing any interference with the through signalling from the extension connected. Contacts of the night key disconnect this portion of the circuit when extensions are put through on night service.

The dial, where required, is not associated with the operator's circuit, as in the smaller switchboards, but is connected via a second key in the cord circuit. Make-before-break contacts on this key, on the dialling side, prevent any momentary disconnection of the exchange line prior or subsequent to the transmission of the impulses from the dial. The other side of the key is used for ringing back on the answering cord. A combined hold and cord test jack is fitted as in the 25-line board.

Multiple Switchboard (C.B. No. 9). In the switchboards previously described the exchange line indicators are of the hand-restored pattern, which are quite satisfactory for single position switchboards.

Where the exchange lines are multipled over several positions, a different circuit is used, incorporating 'self-restoring' indicators. Fig. 46 shows the circuit for the most recent switchboards. Doll's-eye indicators with two windings are used. A.c. ringing from the exchange is rectified and passed through one winding, thereby energizing the indicator. As soon as the 'eyeball' operates, a circuit for the second winding is completed, from earth, via the indicator contact, 1 000-ohm winding, contact of sleeve relay, night key, and night alarm relay to battery.

The direction of rectified current in the line winding is such as to assist the holding coil. When the call is answered from any exchange line jack, the line winding of the indicator is disconnected at the inner springs, the jacks being wired in series, inners to outers

Relay *S* in the line circuit is operated in series with the make

spring of jack, sleeve conductor, and cord circuit *S* relay, which also operates. A contact of the former relay disconnects the holding coil of the calling indicator, which restores to normal.

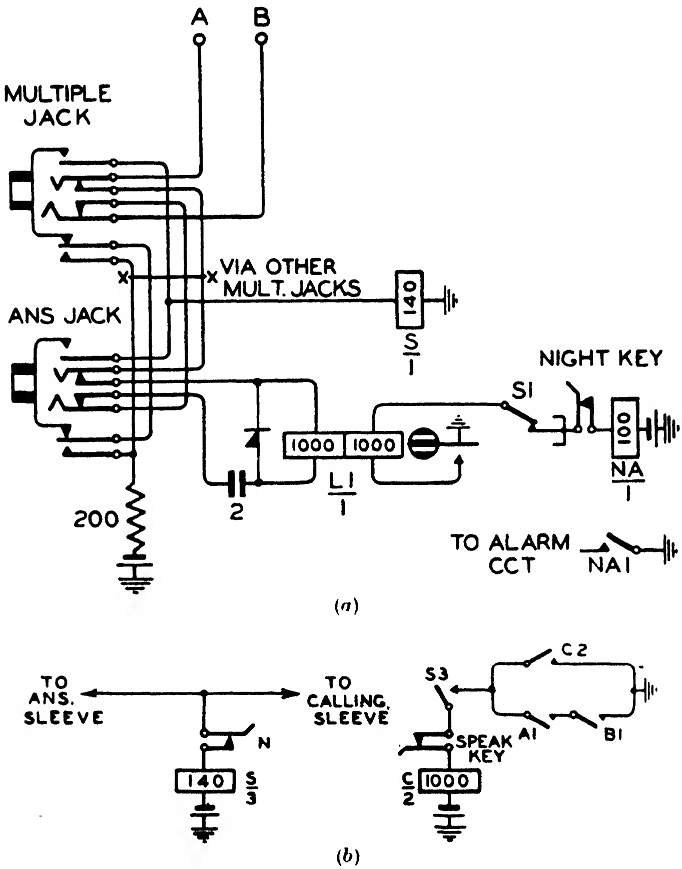


FIG. 46. C.B. NO. 9 P.B.X. SWITCHBOARD
(a) Exchange line circuit.
(b) Difference in cord circuit from 65-line board.

Engaged test conditions (battery potential on sleeve) are placed on the bushes of the other multiple jacks associated with the particular exchange line, via contacts on the jack in which the call is completed.

The extension line jacks are connected as in the 65-line board, except that as there will be several multiple appearances,

the jacks for each line are wired in series, the indicator being connected to the inner springs of the last jack.

The cord circuit is almost identical with that for the 65-line board. Owing to the use of a sleeve relay in the exchange line circuit, relay *C* in the cord circuit cannot be connected directly to the sleeve for its earth, and a separate *S* contact is added instead.

Negative supervision, through clearing, dialling from the cord circuit, and night service on any extension, are standard facilities. The operator's circuit includes provision for the reduction of side tone, and is similar to the circuit used at main common battery exchange A-positions (*q.v.*).

Multiple Switchboard (C.B. No. 10). This is a lamp signalling equipment identical with that used for the smaller common battery exchanges. A combined M.D.F. and I.D.F. is usually fitted, and a power ringer, which is started up from contacts on the ringing keys.

A secondary cell battery, in duplicate, with the necessary charging plant, is also installed.

No through clearing or night service facilities are given, since trained operators will be in constant attendance on such installations, which may cater for 100 exchange lines and 1 000 extensions, being larger than many main exchanges.

Distribution. The exchange and extension lines at P.B.X.'s are equipped with the standard type of protector when the lines leave the building, but internal distribution is effected by means of distribution cases, mounted on walls. Cables terminate on small connection strips, and short flexible jumpers are used to effect the desired distribution.

Ringing Supply. A hand generator is always fitted on each position at a P.B.X., but in the larger equipments, arrangements can be made to extend ringing from the main exchange over a pair of wires, a resistance lamp being connected in series with the ringing lead at each end of the circuit, to guard against external faults affecting the exchange supply. Where power ringing is used, a separate key is provided to change over to the hand generator when required (see also page 82).

Power Supply. P.B.X.'s of the multiple type are equipped with secondary cell batteries, as the load is too heavy for primary cells.

The smaller boards may be served by batteries of primary cells (wet or dry), and in these cases the battery must be of such a capacity that the voltage does not drop below 12 when the maximum load is being carried. Since the battery supplies current for talking purposes, its internal resistance will cause alternating e.m.f.'s to be produced at its terminals, which in turn will result in the superimposing of speech currents in any other circuit connected. This would give rise to serious overhearing trouble, and to minimize the difficulty an 8 μF. or 10 μF. 'reservoir' condenser is connected across the busbars, and acts as a low impedance shunt on the battery.

Power Leads. Power for operating the P.B.X. may be drawn from the battery at the main exchange under favourable conditions.

If external plant is available, a conductor may be connected to the battery busbars at the main exchange (either direct or via counter-e.m.f. cells), and terminated on the battery busbar at the P.B.X., the other busbar being earthed through as low a resistance as possible.

A limitation is set by the resistance of the power lead itself, and the minimum voltage required at the P.B.X.

Assuming that 12 volts is the minimum permissible voltage, and that each extension has a loop resistance of 150 ohms, including the instrument, the current taken by an extension to extension call under conditions of extreme load will be—

(*a*) $$\frac{12}{80 + 80 + \dfrac{20 \times 50}{20 + 50} + \dfrac{150}{2}} = 48 \text{ mA. for a cordless board;}$$

(*b*) $$\frac{12}{80 + 80 + \dfrac{1}{2}\left[\dfrac{20 \times 30}{20 + 30} + 150\right]} = 50 \text{ mA. for a 25-line board;}$$

(*c*) $$\frac{12}{80 + 80 + \dfrac{1}{2}[33 + 150]} = 47 \text{ mA. for a 65-line board;}$$

Therefore, by assessing the maximum simultaneous number of extension to extension calls likely to be set up, and allowing, if necessary, for the connection of the operator to one extension, the current load under extreme conditions can be determined.

(It should be noted that exchange calls take no current from the battery, except for the sleeve relay in the 25- and 65-line boards. Extension calls are therefore the deciding factor.)

If the maximum number of connections is N, and the current taken by each (at minimum voltage) is I amperes, the total consumption will be NI amperes.

Now the main exchange power lead voltage may be—

(*a*) 50 volts or 30 volts if automatic;

(*b*) 40 volts, 30 volts, or 22 volts if manual common battery. Call this voltage V. Then the maximum voltage drop permissible in the power lead is $(V-12)$ volts.

The current under these conditions is NI amperes; therefore the resistance of the power lead must not exceed $(V-12)/NI$ ohms. If this condition cannot be met with one conductor, several conductors may be bunched, or the lead transferred to a higher voltage tapping at the exchange. It should be noted, however, that under light load conditions the voltage at the P.B.X. will rise to a value approaching that of the exchange, and the difference in transmission on extension calls between low load and full load on the P.B.X. must not be so marked as to cause comment from the extension users.

CHAPTER IV

TELEPHONE APPARATUS

THE most important of the apparatus items used in the circuits dealt with up to the present will now be described.

Telephones. Various types of telephones are in current usage, but the table instruments, with hand microtelephones, are the most frequently met.

The transmitter and receiver are contained in the hand-set, which is connected to the body of the instrument by a three-conductor flexible cord. The induction coil and gravity switch are contained in the bakelite moulding of the pyramid-shaped base, which in some instances is fitted over a suitably shaped bell box, containing the remainder of the terminal apparatus, to form a complete telephone set. An example is shown in Fig. 47A.

A wall pattern instrument (see Fig. 47B) may also be fitted with a bell receiver, and a separate transmitter mounted on a front bracket. The circuit used is similar to that of the table instrument, and the same components are employed. Where extension telephones are connected on an intercommunication basis, a separate bell-set, with switch combined, is fitted as part of the installation.

In all cases where overhead conductors are used to connect the subscriber to the exchange, a line protector is fitted, to afford immunity from damage to the telephone instrument should the external line come into contact with a power circuit, or be struck by lightning. Fig. 49 shows the type usually employed.

If a high resistance external contact causes a steady current of more than 250 mA. to flow in the line, the telephone instrument windings would become heated and would ultimately catch fire. The line conductors are therefore taken through heat coils, which consist of a winding of fine wire, of about 5 ohms resistance, on a brass stem. A current of 500 mA. flowing for less than a minute will produce sufficient heat to melt a fusible metal link, which causes the spring holding clips to fly apart, and disconnect the circuit. For protection against

FIG. 47A. TABLE TELEPHONE
(*Siemens Bros. & Co. Ltd.*)

FIG. 47B. WALL TELEPHONE
(*Siemens Bros. & Co. Ltd.*)

currents of larger value, line fuses, which operate without delay at about 3 amperes, are fitted. The carbon blocks serve to give protection against lightning or contact with high voltage power

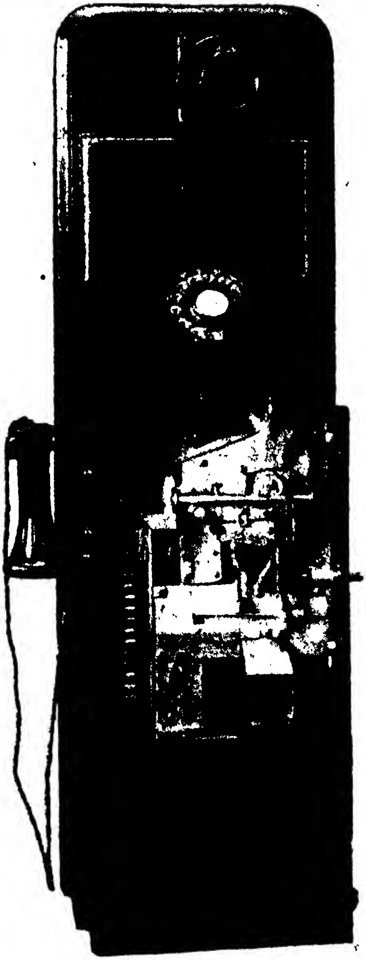


FIG. 48. COIN BOX TELEPHONE—AUTOMATIC

circuits. The inside blocks bear against an earthed metal frame, and the outside blocks are in contact with the line springs. The two blocks of each pair are separated by a thin sheet of

mica or a layer of insulating varnish, but when the line conductors are raised to a high voltage, sparking occurs between the blocks, and the current surge punctures the insulation, and passes to earth via the air gap. The line fuse then operates to disconnect the apparatus, if a sufficiently heavy fault current flows. Where underground cables are used entirely for the connection to the exchange, a terminal block only is fitted at the subscriber's premises, to provide a convenient disconnecting point for fault localization.

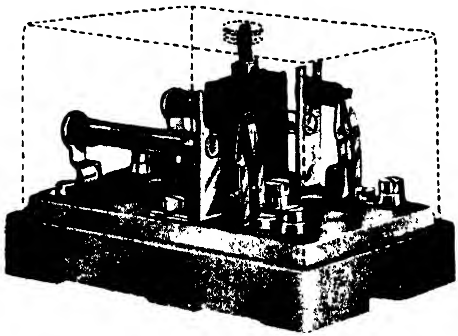


FIG. 49. PROTECTOR
(*Siemens Bros. & Co. Ltd.*)

For calling extension telephones, a trembler bell and push button is employed where the extension is in the same building, and the current for operation may be drawn from the exchange line, or from a local two-cell battery. Where the extension is external, a hand magneto generator is employed. This consists of an H-shaped armature, wound with fine copper wire, rotated at about 1 000 r.p.m. between the two poles of a permanent magnet by means of hand-operated gear, and some 70 volts a.c. can be produced by this means. A centrifugal cut-out is fitted which comes into operation to make or break the local circuit, when a critical turning speed is exceeded. A typical instrument is shown in Fig. 50.

The polarized bell (or magneto bell) is the standard device for receiving signals at subscribers' premises, since the d.c. trembler bell is insensitive, and unsatisfactory when worked with a.c. The polarized bell is connected in series with a condenser of 1 μF. or 2 μF. capacitance to prevent d.c. flowing in the circuit while the receiver is on the rest, and at the same time to offer a reasonably low impedance to the alternating ringing currents.

The bell circuit is generally permanently connected across the line, since its presence occasions but small loss in speech

efficiency, while the provision of switch contacts to remove it would add both to the complication of the instrument circuit and to the fault liability.

The bell itself consists of a U-shaped electromagnet wound with two 500-ohm coils, and polarized by a permanent magnet placed behind them. The armature is pivoted below the poles as shown in Fig. 51.

The polarity of the induced poles is such that the arma-

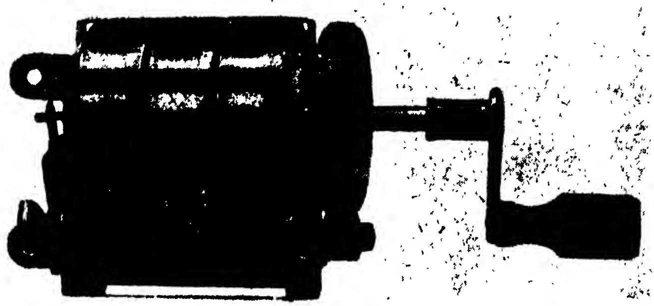


FIG. 50. HAND GENERATOR
(*Siemens Bros. & Co. Ltd.*)

ture comes to rest in one of the extreme positions where the hammer is just clear of the gong. The armature is prevented from sticking to the pole-piece by a small brass pin inserted in the latter. Passage of d.c. through the coils in one direction will cause the armature to be held over permanently to one side, and a reversal of this d.c. will result in the armature moving over to the other extreme position. The reason for this movement can be seen if the polarity of the windings is worked out for each direction of the current. The rapid reversals of current during the application of ringing from the exchange cause the armature to make one complete vibration per cycle of alternating current, and the overthrow of the hammer allows the latter to strike the gongs alternately. The instrument is quite sensitive and will work satisfactorily in series with the condenser over lines of several thousand ohms loop resistance when the standard ringing voltage (70 r.m.s.) is applied.

Exchange Apparatus. On P.B.X. and Main Exchange switchboards plugs and cords are utilized for setting up the connections, the subscribers' and junction lines being con-

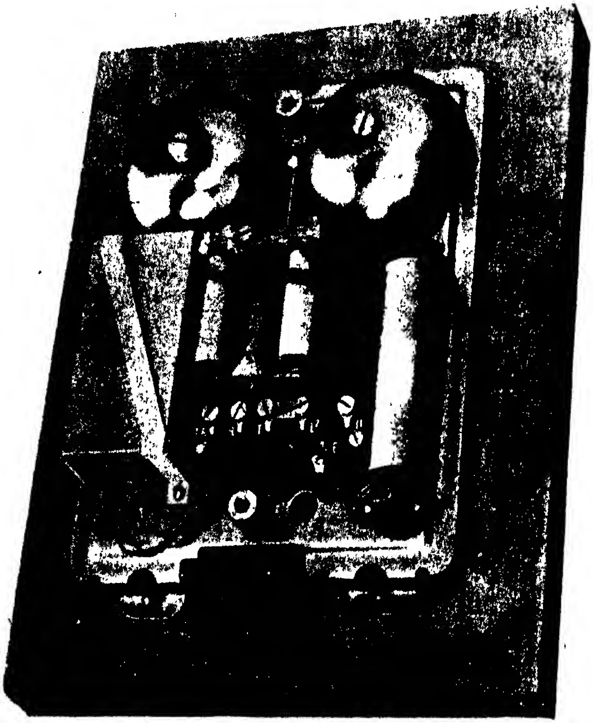


FIG. 51. INTERIOR OF BELLSET
(*Siemens Bros. & Co. Ltd.*)

nected to jacks in the multiple or answering fields. Indicator signals are employed at P.B.X. installations, and lamp signals at main exchanges. The most important of the items concerned in the circuits dealt with in the following chapters will first be described, so that the circuit functions may be more readily followed. Only the main points of design will be

mentioned, and the apparatus should be inspected if the detailed construction of the various types is required. Relays are dealt with separately in a later chapter, as their design is dependent on particular circuit requirements which must first be appreciated.

Fig. 52. Switchboard Lamp
(Siemens Bros. & Co. Ltd.)

Switchboard Lamps. These are of the small tubular type (Figs. 52 and 53) and may have carbon or metal filaments. The former have the following characteristics—

Voltage	Current (mA.)	Use
12	117	Supervisory, 22- and 24-volt Exchange.
24	107	Calling, 22- and 24-volt Exchange.
36	75	Supervisory, 40-volt Exchange.
40	68	Calling signal 40-volt Exchange.
50	100	General use, 50-volt Exchange.

The 6-volt lamp has a metal filament, and consumes only 40 mA. at normal brilliance. It is widely used for switchboards, where current economy and avoidance of excessive heat dissipation are important.

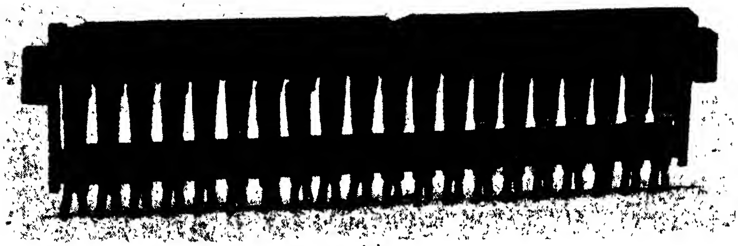
Lamps are mounted in spring jacks, in strips of ten or twenty and may be combined with designation strips consisting of translucent labels, or have separate designation strips associated.

Switchboard Jacks. These are divided into two classes *branch* jacks and *break* jacks. With the former, the tip ring and sleeve of the plug, when inserted, merely make contact with the relevant springs of the jack; but with the latter, the insertion of a plug causes certain springs to break contact with others, and so disconnect a portion of the circuit.

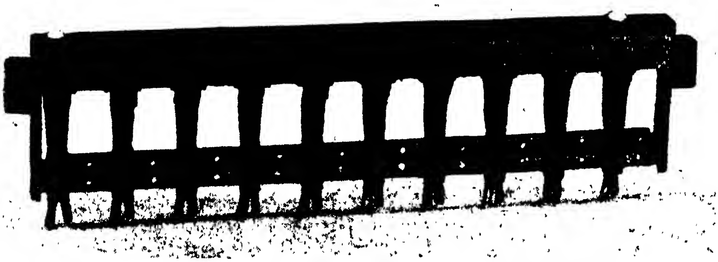
Jacks are mounted singly, or in strips of ten or twenty. They are described by the number of spring conductors, e.g. three-point, five-point, or eight-point.

The construction is shown in Fig. 54, and the use of the different types is made clear in the various circuits described later.

Strips of jacks are numbered from 0 to 9 or from 0 to 19, the

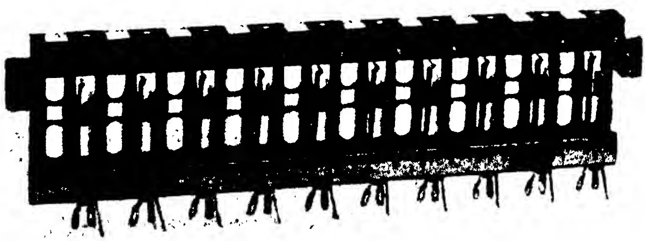


(*a*)

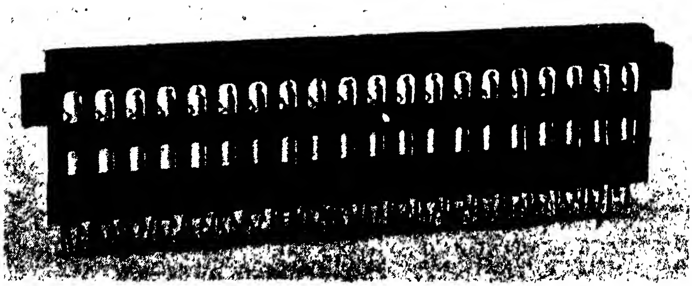


(*b*)

FIG. 53. LAMP JACKS (*a* AND *b*)
(*Siemens Bros. & Co. Ltd.*)



(*a*)



(*b*)

FIG. 54. SWITCHBOARD JACKS (*a* AND *b*)
(*Siemens Bros. & Co. Ltd.*)

latter numbering being used for multiple fields, which commence with 00 in the top left-hand corner of each block of 100, and end with 99 in the bottom right-hand corner.

Labels may be associated with individual jacks when the latter are in strips of ten, and may indicate the calling subscriber's number when used for answering equipments.

FIG. 55. SWITCHBOARD PLUG

Switchboard Plug. Fig. 55 shows the type of plug used on switchboards. It is provided with an insulated thick metal ring or collar, *A*, in addition to the ordinary ring of the three-point plug. This ring is provided to prevent the possibility of the tip and ordinary ring being short-circuited when the plug is passing through the socket of the jack. Fig. 56 shows a section of this plug, and indicates how the conductors *T*, *R*, and *S* of the three-way cord are connected to the plug.

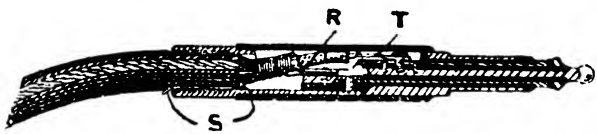


FIG. 56. SWITCHBOARD PLUG
Section.

Connecting Cords. The flexible connections required for the connecting plugs have conductors of thin stranded wires, copper or brass tinsel (Fig. 57).

Each of the conductors is insulated with wrappings of silk, and then covered with a braiding of soft cotton. The external cover consists of glazed cotton coloured red, black, green, etc., for ease in distinguishing between the different circuits set up on a position; both cords of a pair being similarly coloured, to correspond with the key controlling the particular cord circuit.

Repeating Coil. This term is used to describe a line transformer as employed in a cord circuit transmission bridge or in a relay set terminating a junction. There are usually four equal windings wound toroid fashion, with a circular ring of soft iron wire or stampings for a core. This method ensures good balance.

between the windings, as the magnetic circuit is uniformly disposed so far as each winding is concerned.

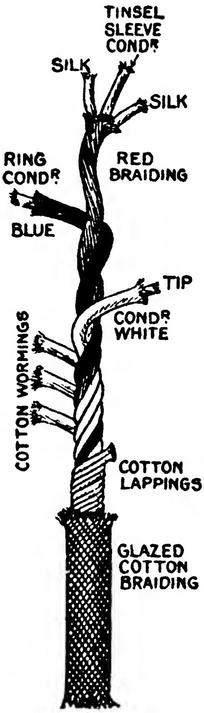


Fig. 57
Switchboard Cord

Resistors. Resistance may be introduced into circuits in various forms.

The most common type consists of a small brass spool with bakelite end-plates, between which is wound sufficient resistance wire (Eureka, manganin, etc.) to produce the required resistance. The ends of the wire are terminated on soldering tags fixed in one of the end-plates, and the winding is covered with a layer of empire cloth. These resistors (P.O. No. 12) are mounted on a threaded spindle, and occupy little space in a relay set. Their resistance is correct to $\pm$ 2·5 per cent.

They are not non-inductively wound, but the inductance is generally so small as to be negligible. The dissipation must not exceed 2 watts, otherwise there is a risk of burning. Where the dissipation exceeds this figure, a different type (P.O. No. 9) is used. This consists of a solid cylindrical porcelain or Steatite spool, on which the resistance wire is wound in a single layer in direct contact with the air. The dissipation may be as high as 15 watts. An earlier type of resistor (P.O. No. 1) consisted of a flat rectangular micanite framework on which the resistance wire was wound, and then enclosed by sheets of micanite, held in position by the metal clamps, which served in addition as connectors to the winding and as fixing bolts. These resistors occupied little space, but were not suitable for mounting in relay sets. Where convenient, resistances may be wound over the inductive windings of relays, especially where the resistance is needed in the relay circuit (e.g. the *G*-relay of a group selector). Economy in space and wiring then results.

Where the heat dissipated under fault conditions is liable to be excessive, several resistors arranged in series-parallel may be used (e.g. operator's meter circuit).

The resistance wire used has a large temperature coefficient, and this must be allowed for if the resistor is to carry current for a long period. Different types are shown in Fig. 58.

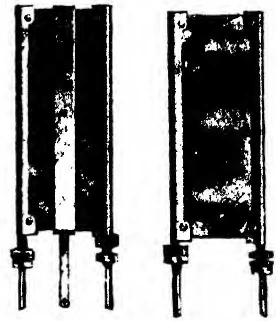


FIG. 58. RESISTORS
(*Siemens Bros. & Co. Ltd.*)

Inductors. An inductor is a coil inserted in a circuit to impede the passage of alternating current. It consists of a winding of a large number of turns of copper wire on a soft-iron core, and may be in the form of a relay without springs. In exchange power circuits, inductors, or chokes, are inserted in series with the battery feeds to machines, so that minor voltage variations at the machine terminals do not produce varying potentials on the exchange busbars, and thus affect other circuits. Inductors are also known as *retardation* or *impedance* coils. Their essential feature is a high value of inductance, the resistance being arranged to suit the needs of the particular circuit. They are much used in filter circuits where, in conjunction with the correct capacitance, a circuit resonant at any desired frequency may be obtained.

Indicators. An indicator is an electromagnetic relay, with a shutter or 'eyeball' in place of the spring-set. Indicators are used mostly at subscribers' premises, where battery power is not available for lamp signals, and take various forms. Three types in general usage are—

(*a*) The *doll's-eye* indicator, Fig. 59, consisting of a pivoted 'eyeball' and an iron core carrying the winding, the whole being mounted in a light metal framework.

When the coil is energized, the eyeball rotates and displays the number of the line with which it is associated, in the front opening. The rotation of the eyeball also closes a light contact, which may be used for alarm purposes. When the current is cut off, the eyeball is restored by gravity, i.e. the indicator is self-restoring.

(*b*) The *a.c. drop* indicator, Fig. 60.

This indicator is of high impedance, and is designed for direct connection across the A- and B-wires of a subscriber's line at a P.B.X., without introducing any serious transmission

loss. The coils consisting usually of two 500-ohm windings, are wound on an iron core and contained in a cylindrical iron case, the open front end providing the gap in the magnetic circuit

FIG. 59. 'DOLL'S-EYE INDICATOR'

to which the hinged armature is attracted when the coils are energized. The movement of the armature raises a long lever which releases the rectangular flap at the opposite end of the coil. The indicator is mounted so that the flap is displayed to the exchange operator, and it must be restored by hand. A local contact is fitted for alarm purposes.

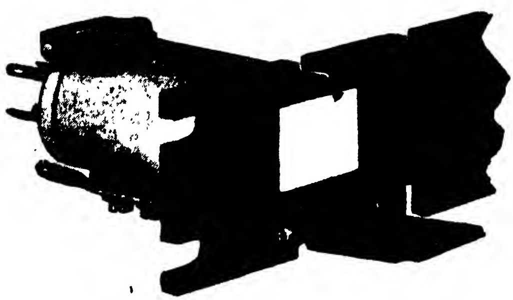


FIG. 60. A.C. DROP INDICATOR
(*Ericsson Telephones, Ltd.*)

(*c*) The *disc signal indicator*. This indicator, when mounted vertically, displays a circular white disc when operated, and a dark background normally. It is used in keyboards to give a negative supervisory signal, but may also be mounted

horizontally for use as a calling signal. The construction is shown in Fig. 61. A local contact is operated when the armature is attracted.

FIG. 61. DISC INDICATOR
(*General Electric Co. Ltd.*)

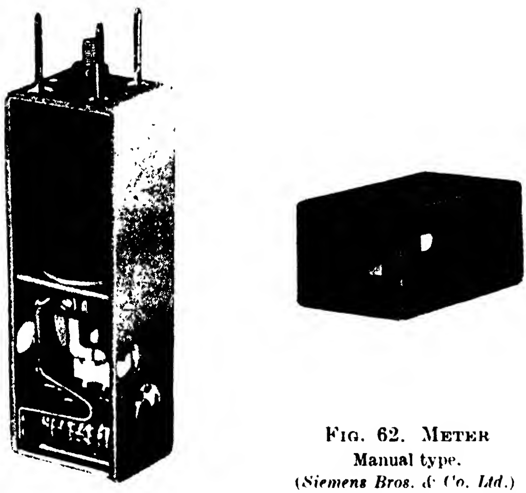


FIG. 62. METER
Manual type.
(*Siemens Bros. & Co. Ltd.*)

Meters. Two types of meter are in use. In manual exchanges that shown in Fig. 62 exists in large quantities, whilst the smaller type (P.O. No. 100), shown in Fig. 63, is now installed in automatic exchanges.

Both types are somewhat similar in operation. Number discs are operated to display in a small window the total calls registered, and the units wheel is stepped one position ($\frac{1}{10}$ revolution) for each operation of the armature.

A spring restores the armature to normal, and a test jack is usually provided, to verify the correct registration of calls, on

the meter rack. A local contact is fitted, the function of which can be seen from the circuit diagram. The coil resistance may be varied to suit the particular requirements.

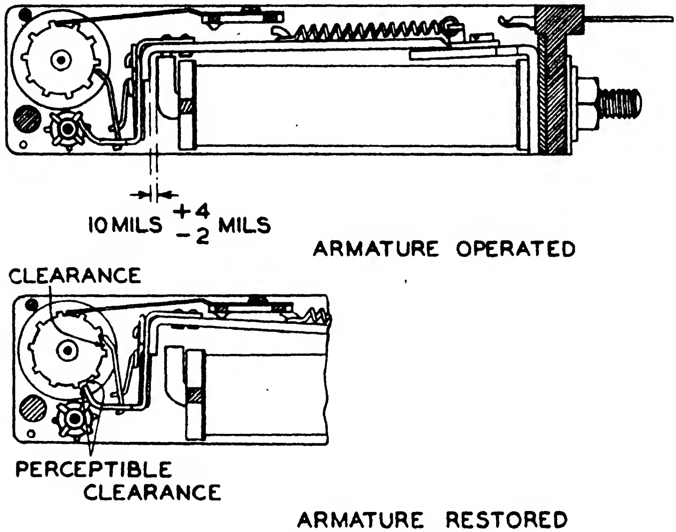


FIG. 63. "100" TYPE METER

Keys. There are two main types of key in current use—
(*a*) *lever* keys;
(*b*) *press button* keys.
Either may be of the locking or non-locking type. The lever pattern is used for the operator's speaking and ringing keys, in P.B.X.'s, and on test desks.

The press-button type is used for order wire keys, meter keys, and in all cases where space is limited.

The various types are illustrated in Fig. 64. Contact assemblies of breaks, makes, changeovers, or make-before-break changeovers, can be fitted and the symbols used in the circuit diagrams indicate which type is employed for particular purposes.

Ringing and Tone Vibrators. In the smallest telephone exchanges, ringing and tone generators are not supplied, their place being taken by vibrating relays.

On the ringing vibrator (Fig. 65) the reed is weighted by an iron armature to give a natural period of oscillation of about $\frac{1}{20}$ sec., and consequently alternating current at 20 cycles per

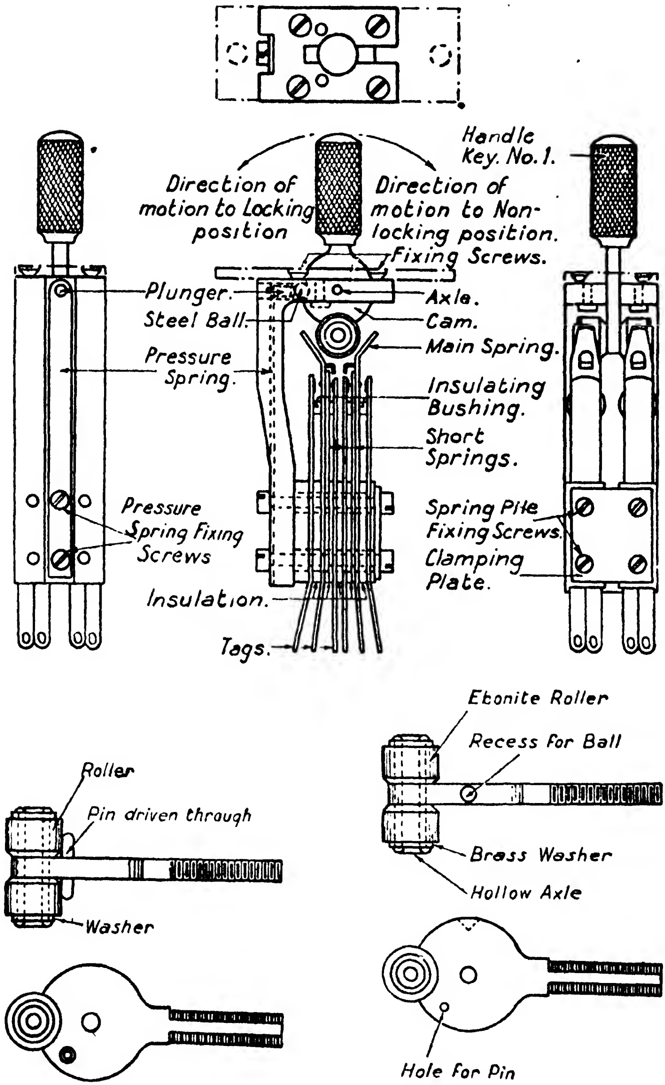


FIG. 64. LEVER KEYS AND O.W. KEYS

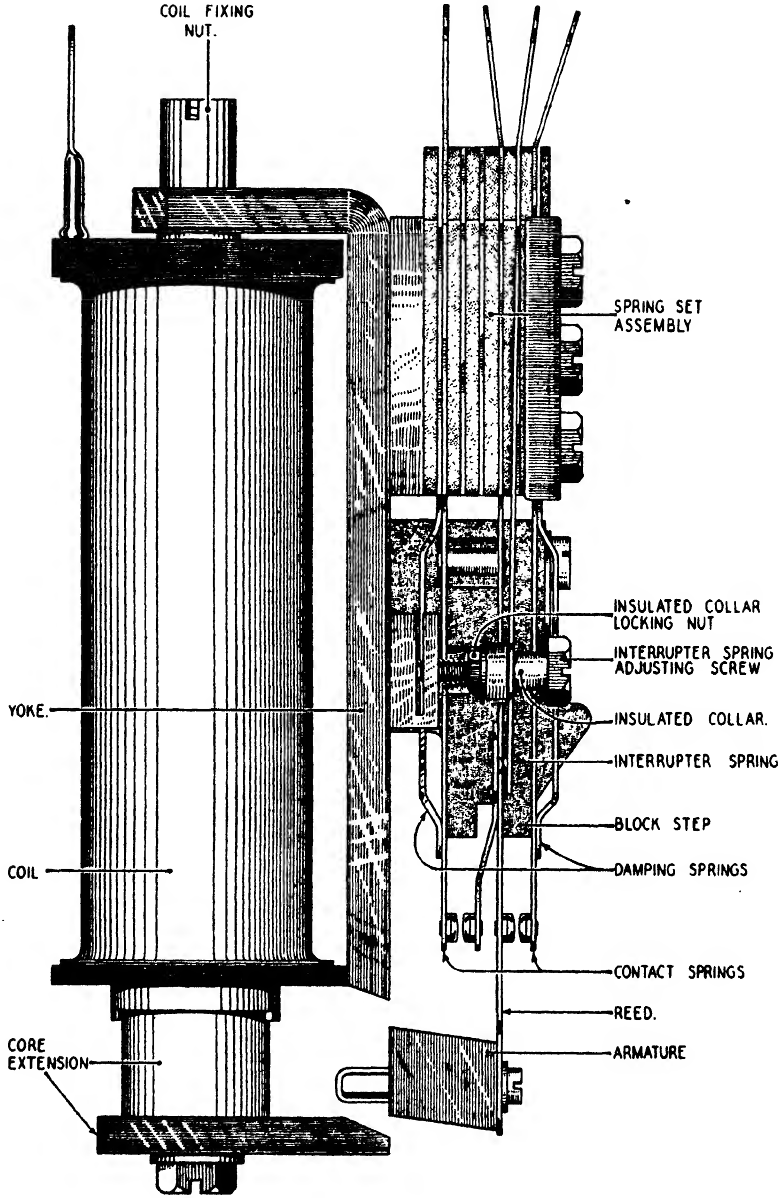


FIG. 65. RINGING VIBRATOR

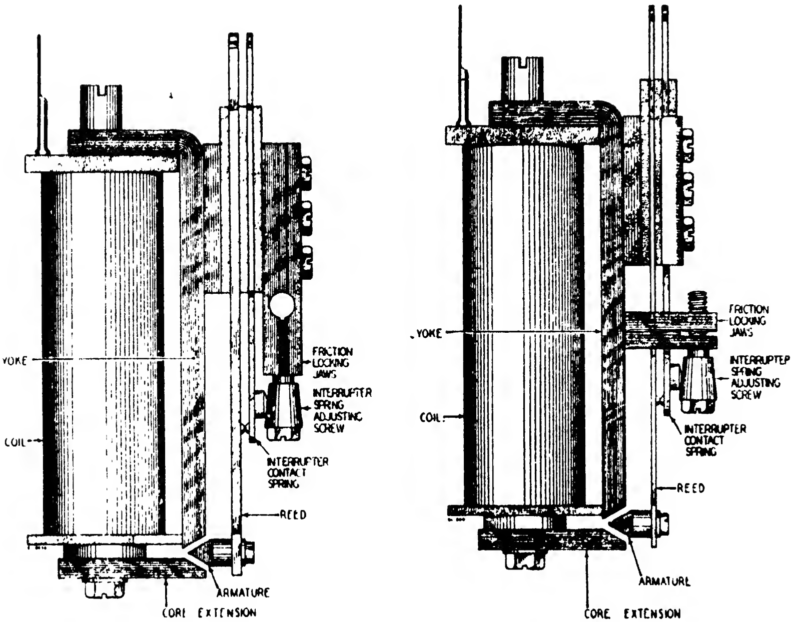


FIG. 66. TONE VIBRATOR

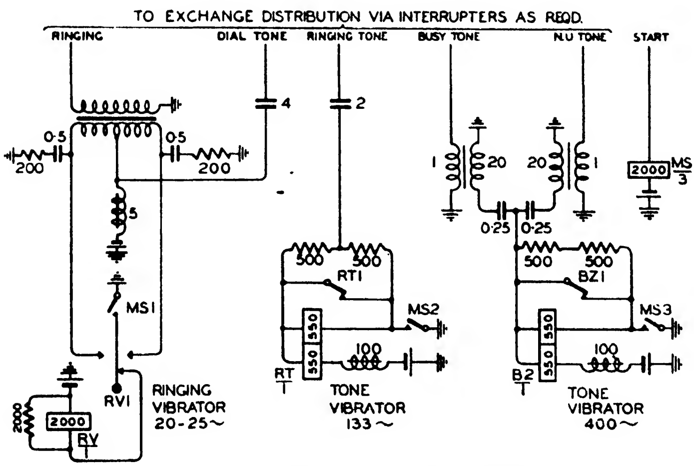


FIG. 67. RINGING AND TONE CIRCUIT

sec. can be produced by a suitable circuit. The relay is self-driven via its own interrupter contacts, when the external circuit is completed by a 'start' contact. The method of production of alternating current will be clear from Fig. 67. The circuits for each half of the primary winding are completed alternately by the vibrator contacts, and for each complete make and break in the primary a whole cycle of alternating current will be induced in the secondary.

The tone vibrator is of similar construction, but the reed is stiffer, so as to vibrate at a higher frequency. The two standard tones are 133 pulsations per second (p.p.s.) (ring back tone) and 400 p.p.s. (n.u. and busy tone), and a slightly different construction is used for each (Fig.66). In the case of tone vibrators where no separate contacts are used in the tone circuit, the current produced is not large, and the interrupter springs serve the dual purpose of controlling the relay operation and producing the current variations for tone purposes. Variations in the potential at the junction of the two 500-ohm resistors alter the charge in the condenser in series with the tone lead, or transformer primary, and the pulsating current thereby produced is fed out direct as ring-back tone at 133 p.p.s., or as busy and n.u. tone from transformer secondaries at 400 p.p.s.

Ringing Supply to P.B.X.'s. In the case of larger subscribers' installations, where multiple switchboards may be used, the ringing supply is obtained from a small ringing generator at the subscriber's premises. The machine will be run from the mains or the P.B.X.. battery, and is similar in construction to the type employed in main exchanges (see Chapter IX). As the load is very uneven compared with a public exchange, it is usually the practice to control the running of the machine from a "start" contact in the P.B.X. cord circuit. This contact may conveniently be situated on the ringing side of the 'Speak and Ring' key, and as the latter is non-locking in the ringing position, a special 'Start' circuit is employed. The key contact may energize a mercury switch type of relay, which completes the motor circuit and locks the relay in the operated position. The release of the relay will be delayed for a period of several seconds, so that further operation of the cord circuit ringing key, which may be necessary before the particular extension has answered, will not cause undue sparking

and wear of the key and relay contacts. The 3-second cam of the machine may be used to control the release, or this may be achieved with slow-acting relays. In installations of this kind the greatest care must be taken in running the leads between the switchboard, ringing machine, and main batteries, otherwise induction will occur between the ringing and battery-feed circuits, and the commutator hum will be superimposed on the switchboard bus-bars, and will cause interference on all calls.

A.C. Mains Systems. It is possible to utilize 50-cycle A.C. supplies to ring magneto bells, and a system is in use in which the mains supply is transformed down to 75 volts, the centre-point of the secondary winding being earthed. A 50-volt lamp is inserted in each ringing lead to safeguard the transformer, and the standard magneto bell is readjusted to give optimum results.

A frequency transforming device, known as a sub-cycle ringer, is also coming into use. A circuit consisting of an inductive A.C. relay, a condenser, and the primary winding of a transformer in series is tuned to be resonant at one-third the frequency of the A.C. mains, i.e. $16\frac{2}{3}$ c.p.s./500. The secondary of the transformer supplies current at this frequency, and about 75 volts to the ringing commons, while the resonant circuit is energized from the mains *via* a choke coil. Every third positive peak on the mains side coincides with successive positive peaks at the lower frequency, and every third negative peak with corresponding negative peaks, the voltage peaks of the intermediate cycles being opposed or assisted by the rise and fall of voltage in the resonant circuit. The function of the relay is to short-circuit the choke coil until the mains current is switched on, thus allowing a large charge to be given to the condenser to initiate resonance. The relay then operates, and the applied voltage is now reduced by the choke to a value just sufficient to maintain oscillation in the circuit.

CHAPTER V

MANUAL TELEPHONE EXCHANGE CIRCUITS

Manual Central Battery Systems. The central battery, or common battery, system is the most widely adopted manual system of telephony, and installations of this type serve all but the smaller manual exchange areas. Each subscriber's circuit is connected to the exchange by two line conductors, over

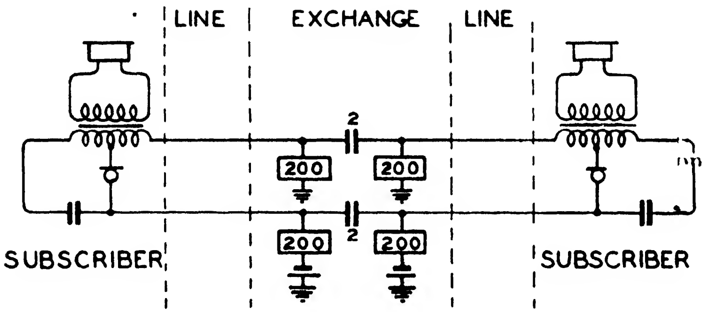


FIG. 68. PRINCIPLES OF COMMON BATTERY WORKING
40-volt system.

which both speaking and signalling currents are passed, an earth connection at each end being used purely for protective purposes. Fig. 68 shows the general principles of working.

The subscribers' lines are terminated on jacks on the switchboard, and may be interconnected by means of cord circuits, which supply current for speaking and supervisory purposes.

A secondary cell battery, of 22 or 40 volts, is situated at the exchange, and provides a source of power for the whole telephone area served. The battery is usually provided in duplicate, as explained in Chapter IX.

Before the circuits are analysed, the principles of speaking and signalling will be stated.

Direct current, for use as a 'carrier' for the speech currents, is essential to the working of the C.B. Transmitters. It is fed out to the calling and called subscribers from the connecting cord circuit, via balanced battery feeding bridges. These same

bridges are adapted to serve as signalling units, to give supervisory signals to the controlling operator, and to pass them on, if necessary, to a distant exchange.

The subscribers call the exchange by means of a 'loop' applied to the line conductors, and clear by giving a disconnection. This is the standard condition for both manual and automatic working. A line relay, with earth return, is used to pick up the calling loop and translate it into a lamp signal at

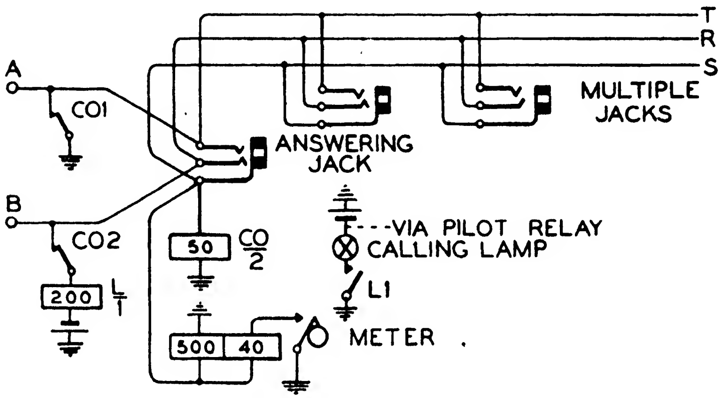


FIG. 69. C.B. SUBSCRIBER'S LINE CIRCUIT

the exchange, and cord circuit relays respond to the disconnection on clearing, giving a lamp signal to the operator.

To call the subscribers from the exchange, alternating currents of low frequency (15 to 25 cycles per sec.) are used. A polarized bell at the subscriber's premises responds to these currents, and a condenser inserted in series with the bell allows the normal disconnection condition to obtain, whilst permitting the passage of alternating ringing currents.

Subscriber's Line Circuit (Fig. 69). The two line conductors are connected to the switchboard jacks via the main and intermediate distribution frames, the functions of which will be explained later. One jack, with its calling lamp associated, is fitted in the 'answering jack field' (see face equipment of position, Fig. 99) immediately in front of an operator and low down on the panel. The remainder of the jacks are connected in parallel in the multiple, one appearance of which is accessible to each operator.

The A-line is connected to the short spring of the jack, and the B-line to the long spring.

Thus, the usual designations are as follows—

Conductor	Connected to	Normal Condition
A-, or positive, line	Short, or tip, spring of jack	Earthed
B-, or negative line	Long, or 'ring' spring of jack	Battery

The battery and earth conditions are fed via contacts of a *cut-off* relay, which is itself earthed and connected to the third jack spring. This third connection, which is used only in the exchange portion of the subscriber's apparatus, is termed the *test* or *third* conductor. It is connected to the *bush* or *sleeve* of the jack, hence the nomenclature 'tip, ring, and sleeve' or 'positive, negative, and test' when referring to the wiring of the exchange equipment. A fourth wire, for the lamp circuit, is run from a contact of the line relay to the switchboard, via the I.D.F. The battery and earth feed to the subscriber's line at the exchange end is termed a *wet loop* and is unbalanced, i.e. the impedance to earth of each line is not the same.

The operation is as follows—

On the subscriber removing the receiver to make a call, current flows from the battery, line relay coil, B-line, subscriber's instrument, A-line, to earth via the cut-off relay contacts. The line relay is operated, and causes the switchboard lamp to glow, bringing into operation also the pilot relay, which lights a pilot lamp on the panel in which the calling lamp appears, and, if necessary, operates a night alarm circuit.

The operator inserts the answering plug of a pair of plugs and cords into the 'answering' jack associated with the lamp, and the conditions on the answering cord sleeve conductor (*q.v.*) energize the subscriber's cut-off relay. The line relay is thus disconnected, and it releases, extinguishing the calling lamp, and line conductors are connected only to the subscriber's instrument and the cord circuit. All subsequent conditions prior to the subscriber clearing affect only the cord circuit. When the subscriber clears, the plug is withdrawn, and the cut-off relay restores to normal. It is usual for the subscriber's meter to be connected in parallel with the cut-off relay, and

it is shown in the diagram. Its operation will be described with that of the cord circuit.

When a subscriber is called from the exchange, the insertion of a calling plug into a multiple jack energizes the cut-off relay, and leaves only the subscriber's bell and condenser in the circuit. The ringing current therefore has no effect on any apparatus at the exchange.

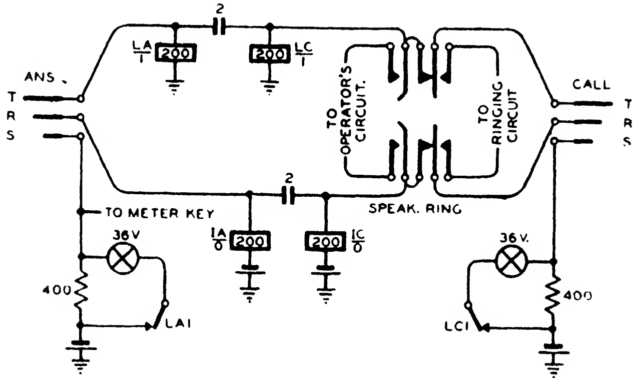


FIG. 70. 40-VOLT 'STONE' SYSTEM
C.B. cord circuit: A-positions.

Cord Circuit (Fig. 70). The tip, ring, and sleeve of the answering and calling cords are connected to the cord circuit apparatus by means of flexible three-way conductors termed *cords*. The battery feed, or *transmission bridge*, which supplies talking and signalling current is joined to the tip and ring of each side of the circuit, and may be of the 'Hayes' (Fig. 71) or 'Stone' type. The operation of the 40-volt Stone system (Fig. 70) will be discussed generally, a comparison of the diagrams indicating the essential differences from a circuit standpoint. The supervisory circuits are connected to the sleeve conductors, and are controlled by relays in the transmission bridge.

A combined speaking and ringing key is provided for each pair of cords to enable the operator to couple her telephone to any circuit on the position.

Operation (40-volt System). When a calling lamp glows, the operator seizes an answering plug (these are at the back, nearer the panel, to avoid unnecessary crossing of cords) and inserts

it into the relevant jack. The battery on the sleeve of the plug operates the subscriber's cut-off relay, and frees the subscriber's line from the calling equipment, the lamp being extinguished.

The subscriber's meter does not operate, as calculation will show that less than five volts are applied.

The *LA* relay (see diagram) operates by current sent out through the impedance *IA* and the subscriber's instrument

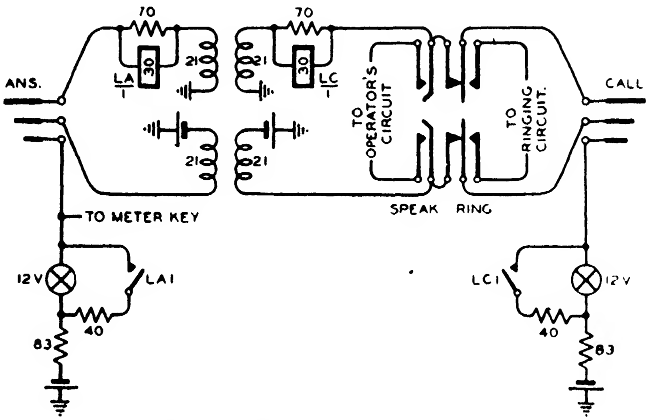


FIG. 71. 22-VOLT 'HAYES' SYSTEM
C.B. cord circuit: A-positions.

loop, disconnecting the answering lamp associated with the sleeve circuit.

The wet loop condition from the answering cord feeds talking current to the subscriber, with whom the operator obtains connection by throwing the cord circuit speaking key, thus putting her telephone circuit across the tip and ring of the calling cord. False operation of the *LC* relay is avoided by placing a condenser in series with the operator's instrument.

The subscriber's requirements having been ascertained, the operator picks up the calling plug of the pair, and inserts it into the required jack (either junction or subscriber), first making the 'engaged test' which is described separately later.

If a junction to another exchange has been picked up, the signalling to the distant end is effected automatically by the wet loop (*LC* relay and *IC* impedance) and the operator merely watches the calling supervisory lamp, which darkens, due to the operation of *LC*, as soon as the distant operator answers.

When direct connection to another subscriber on the same exchange is made, the cord circuit key is thrown over to the non-locking, or 'ringing' side, thereby disconnecting the wet loop and applying ringing current to the called subscriber's line. When the called party answers, relay *LC* operates if the cord circuit key is normal, and by disconnecting the calling supervisory lamp indicates to the operator that the conversation condition has been established.

The replacement of the receiver by either party causes the relevant supervisory lamp to glow. When both lamps are glowing the operator takes down the connection, after having depressed the meter key to register a call to the originating subscriber. Both cut-off relays and meter restore to normal when the plugs are withdrawn, and the cord circuit is available for use on other calls.

A-Operator's Telephone Circuit. The speaking common connections from the keys are taken to the position telephone circuit, shown in Fig. 72. The operator's headgear receiver and breastplate transmitter are connected via a plug and flexible cord to the jack, in the lock rail of the keyboard. The transmitter is fed with direct current via an impedance coil and the primary winding of a transformer. The resistance of the impedance coil limits the current to approximately 100 mA., and a 4 μF. condenser confines the speech currents to the local circuit. The secondary coil has two windings of equal number of turns, but differing considerably in resistance. The connection of the receiver circuit across the higher impedance coil results in a considerable diminution of 'side tone' on the receiver. It will be noted that if the joint impedance of the external lines is approximately equal to the difference in impedance of the two transformer secondary windings (420-ohm), the e.m.f.'s induced in each winding when the operator speaks will be equal, and consequently no current will flow in the receiver. The operator is not therefore inconvenienced by any high level of speech or room noise picked up by her own transmitter and reproduced in the receiver. During reception of speech from the cord circuit, the receiver is, of course, once more effective, although it is now shunted by one half of the secondary winding.

The small rectifiers are placed across the receiver to minimize

the annoyance caused by any heavy induced voltages in the circuit, which would produce loud clicks in the receiver.

The rectifiers act as voltage limiters, i.e. they do not conduct in either direction to any great extent until the voltage exceeds 2·0 volts. At higher potentials, one or the other will short-circuit the receiver and render the surge innocuous. Reception

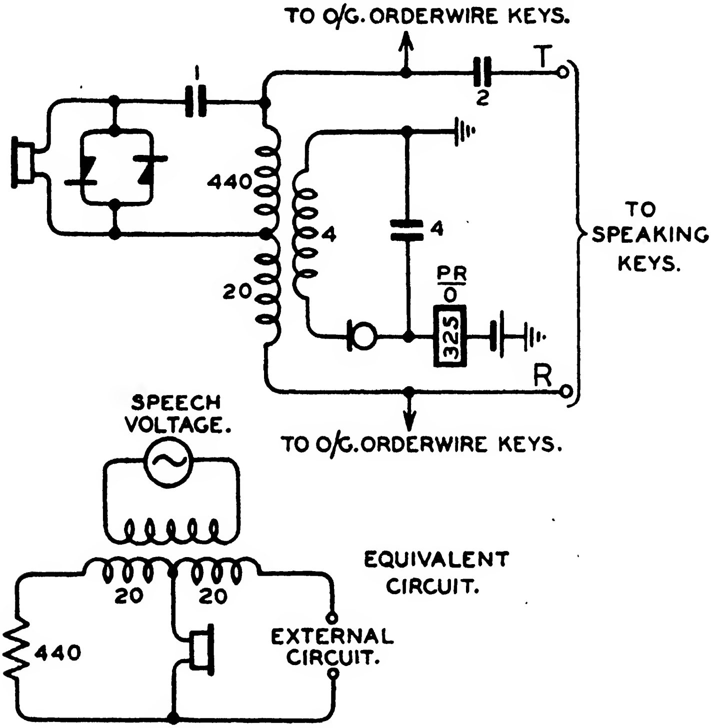


FIG. 72. A-OPERATOR'S TELEPHONE CIRCUIT

of speech is, of course, slightly degraded, but is more than compensated for by the absence of 'clicks.'

Direct current may flow through the secondary winding when the operator is connected to an outgoing order wire, but normally the 2 μF. condenser in series with the winding prevents any flow of current (and consequent operation of the cord circuit supervisory relay) when any speaking key is thrown.

The 1 μF. condenser is inserted to prevent any direct current flowing in the receiver circuit and thereby demagnetizing the magnets.

Engaged Test (Fig. 73). The condenser in series with the operator's telephone is charged up to the full voltage of the exchange battery as soon as the speaking key is thrown. That side connected to the tip of the calling plug is at earth potential, and to make the engaged test, the tip of the calling plug is tapped on to the bush of the jack it is desired to test. If the bush is at earth potential, which is the case when the line or junction is disengaged, contact with the tip of the plug has no

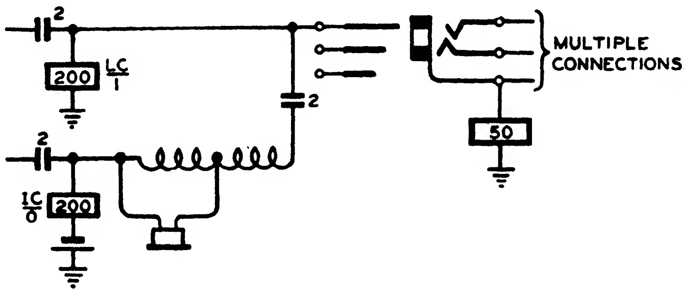


Fig. 73. Engaged Test Condition

effect on either circuit, and the potential across the operator's circuit condenser is not disturbed. The line is then said to test disengaged, and the plug is inserted.

The sleeve circuit of the calling cord is now complete, and current flows through the cut-off relay (or equivalent resistance spool in the case of an outgoing junction) to earth.

The potential at the bush of the jack therefore becomes several volts negative with respect to earth, and this potential appears on every multiple appearance of the circuit in use. If a second operator now tests the bush of a jack multipled to the one first considered, the potential of the normally earthed side of the condenser in the operator's circuit will be lowered suddenly at the moment of contact between the tip of the plug and the bush of the jack. The resultant partial discharge of the condenser causes a 'click' in the testing operator's telephone, and the circuit is proved to be engaged, or 'busy,' without any interference to the call already in progress. The free and busy conditions, and the method of test, can readily be seen from the diagrams.

Metering. When both answering and calling supervisory lamps are glowing (assuming the call to have been effective), the

operator depresses the cord circuit meter key, which is situated in front of the calling cord on the keyboard (Fig. 74).

The meter key connects battery via the 0·4-ohm position meter to the sleeve of the answering plug, and thereby applies full battery potential to the bush of the subscriber's jack. The subscriber's meter operates with the increased voltage on the 500-ohm winding. The meter registers one call in operating,

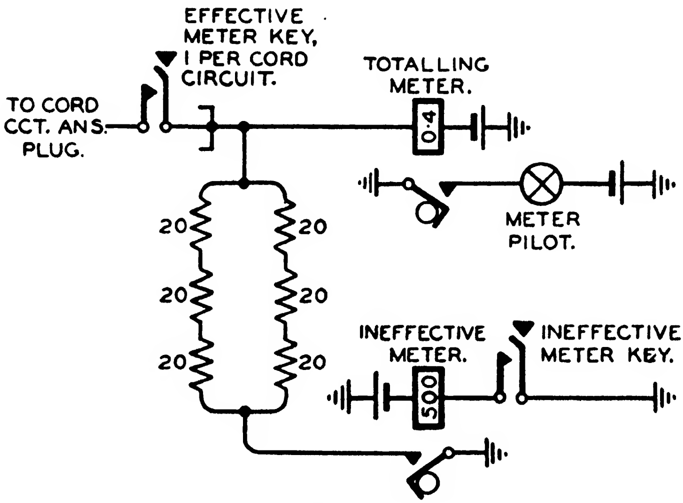


FIG. 74. METERING CIRCUIT

and also reduces the sleeve circuit resistance to approximately 22 ohms.

The resultant increase of current through the position meter results in its operation and registration. A contact on the armature completes the meter pilot lamp circuit, and the operator thereby verifies that the subscriber's meter has functioned. It should also be noted that the short-circuiting of the cord circuit sleeve resistance by the 0·4-ohm position meter causes the answering supervisory lamp to be dimmed so long as the meter key is depressed.

Should the call have been ineffective, the cord circuit meter key is not depressed, but an 'ineffective meter' key on the position is operated.

The circuit for the 500-ohm ineffective meter is completed, and the meter operates, closing a circuit for the effective meter

via a 30-ohm resistance. The effective meter then operates, and causes the meter pilot lamp to glow.

The 30-ohm resistance is made up of six 20-ohm coils in series-parallel, so disposed as to prevent the risk of fire should an earth fault develop on the circuit.

At 22-volt exchanges four additional cells are connected in series with the main battery to provide 30 volts for the metering

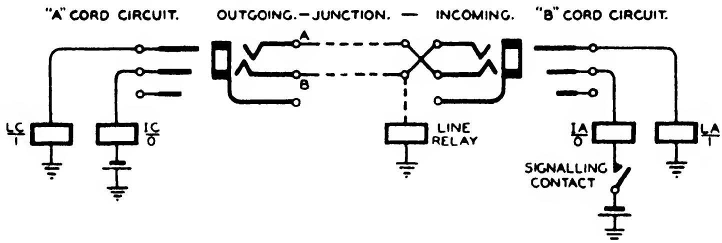


FIG. 75. PRINCIPLES OF AUTOMATIC SIGNALLING JUNCTION

circuit. This increased voltage is also employed on junction cord circuits, to counteract the resistance of the line, which might otherwise limit signalling. The 40-volt system gives sufficient margin without the employment of extra cells.

Junction Working. Junctions between two exchanges are arranged for either *bothway* or *unidirectional* working.

If the group of junctions has less than five circuits, the route is usually worked 'bothway,' i.e. calls can be made over any junction in either direction.

Where larger numbers of junctions are warranted by the traffic carried, it is usually more economical to provide one-way or unidirectional junctions.

Less equipment is required, and a considerable saving of operating time results owing to the shorter testing time required, due to the absence of incoming traffic at the testing end. Where the route is worked on an 'order wire' basis, unidirectional working is necessary in any case.

Unidirectional junctions are divided into outgoing and incoming circuits. The outgoing lines appear only in the junction multiple, whilst the incoming ends terminate on special B-positions, at which the operators deal only with junction traffic. The cord circuits on such positions differ from those used on A-positions by virtue of the additional facility

of 'through signalling.' Calls from subscribers to distant exchanges can be connected to the outgoing multiple over ordinary 'A' cord circuits, since it is necessary for the A-operator only to receive the supervisory signals from the distant end. The A-operator is said to control the call, while the B-operator merely completes connections as requested, leaving them set up until a supervisory signal is received from the originating end.

Jack-ended Junctions. These circuits terminate on jacks and lamps at the incoming end, and are automatic signalling as a rule, i.e. the insertion and withdrawal of the plug at either end results in the transmission of the desired signal

The principles of signalling are—

Calling—battery on B-line from outgoing end;

Answering—battery on A-line from incoming end.

It follows that the incoming terminal apparatus must consist of an earthed relay on the B-line, whilst at the outgoing end the cord circuit must contain an earthed supervisory relay on the A-side (Fig. 75).

To secure these requirements, and to provide for universal working with subscribers or junctions, all C.B. cord circuits are arranged to feed out earth on the tip, through a supervisory relay, and battery on the ring, through some sort of impedance coil. Answering and calling cords are similar in this respect, and to a limited extent are interchangeable.

Since the answering cord feeds out earth on the A-wire, it is a standard practice to reverse the A- and B-lines of an incoming junction at a point immediately prior to connection with the incoming jack. On answering, therefore, the B-operator sends out battery on the A-line of the junction, and connects the earthed cord circuit supervisory relay to the B-line, thus meeting the standard signalling requirements. Outline circuits are shown in Figs. 76 and 77. The cord circuit used for jack-ended junctions contains two relays in series in the sleeve of the answering cord, both relays operating when the plug is inserted into a subscriber's answering jack (low resistance sleeve) but only one when the plug is inserted into an incoming junction jack (high resistance sleeve). Discrimination between the circuits is thereby effected—a wet loop is fed out to a subscriber, to supply current for the transmitter, whilst the battery feed to the ring is withheld when answering

an incoming junction until the B-operator throws the speaking key, and, later, until the called party comes on the line.

Signals from the called subscriber's gravity switch are

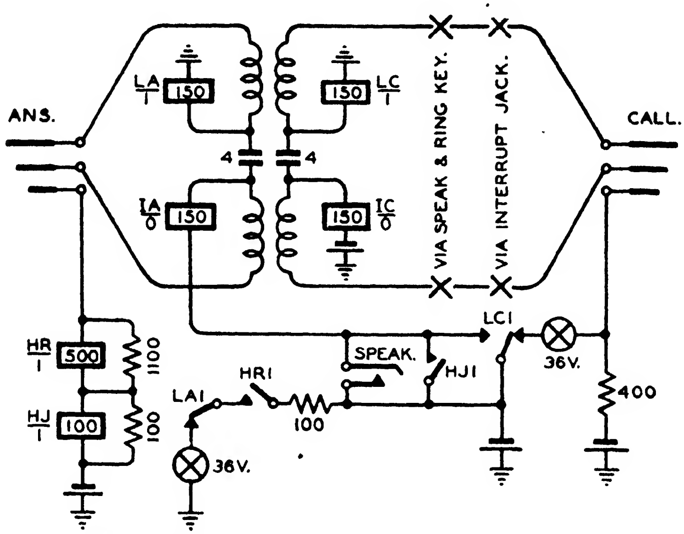


FIG. 76. C.B. 30-VOLT SYSTEM—JACK-ENDED JUNCTION CORD CIRCUIT

(*a*) *HJ* does not operate when answering an incoming junction call.
(*b*) For connections of interrupt jack, see 'Trunk flashing circuit.'
(*c*) Non-inductive shunts on *HR* and *HJ* are to prevent shock to operator on withdrawal of plug.

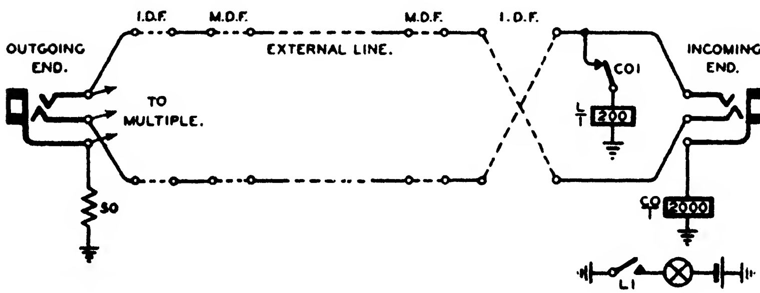


FIG. 77. JACK-ENDED JUNCTION

relayed through the cord circuit to the A-operator, by means of the supervisory relays in the tip of each calling cord.

This facility is termed *through signalling* and can be obtained over several junctions, in tandem, back to the originating operator.

'Forward' through signalling, from the A-operator to an intermediate exchange, is sometimes required, and this feature is dealt with under trunk working.

Jack-ended Circuit (Fig. 78). The line relay *L* operates when the junction is taken into use by the distant A-operator, and causes the calling lamp to glow.

When the B-operator answers, *CO* is energized, *LL* is operated at *CO*2, and *L* is held via a local circuit at *CO*1.

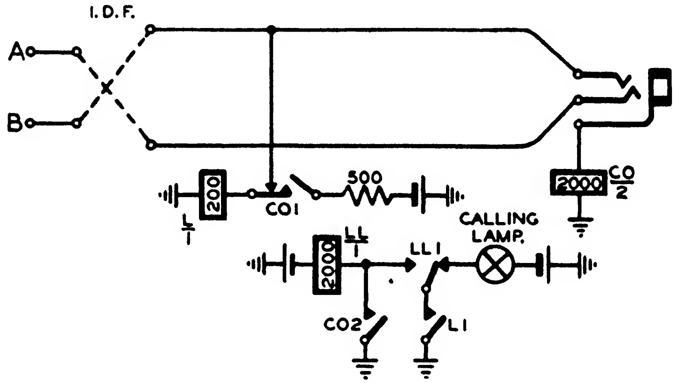


FIG. 78. INCOMING J.E. JUNCTION WITH CALLING LAMP LOCK OUT

On conclusion of the conversation, the circuit is cleared from the outgoing end in the normal course *L*, *LL*, and *CO* remaining operated until the B-operator withdraws the plug. Should, however, the B-operator be the first to clear, *L* does not release, being held from the A-cord circuit on restoration of *CO*1. *LL* is therefore maintained in the operated condition, and prevents a reappearance of the calling signal until the outgoing end of the circuit has been cleared, and taken up again by a following call.

Plug-ended Signal Junctions. The capacity of the keyboard on a B-position is limited to seventeen pairs of cords, and if the traffic which can be dealt with at one B-position exceeds the capacity of this equipment, different methods of handling it must be adopted.

One solution is to make the incoming junctions terminate on plugs and cords; and up to thirty-four junctions per position can be obtained by this means. One supervisory lamp per cord

is provided, and serves also as a calling lamp. A speaking and ringing key is associated with each junction and, on perceiving a lamp glow, the B-operator throws the relevant key, thereby connecting her telephone circuit across the tip and ring of the plug. The call is completed, as before, by inserting the plug in the multiple jack, ringing being sent out from the cord circuit if necessary. This system has the advantage of increased speed of operation over jack ended circuits, but does not allow

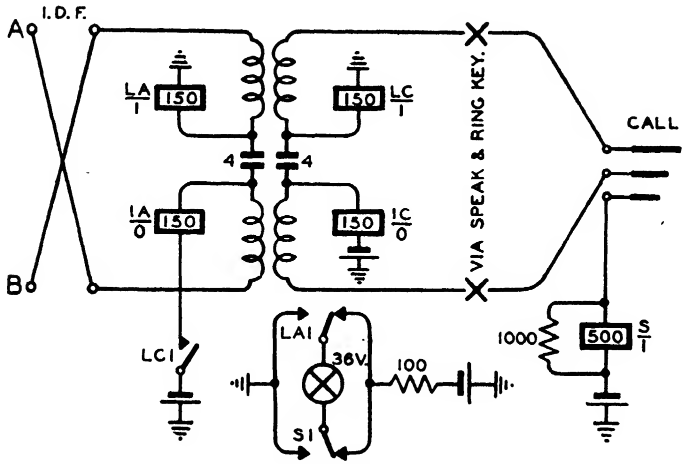


FIG. 79. INCOMING PLUG-ENDED SIGNAL JUNCTION

B-operators to answer subscribers' calls on the same position when the junction traffic falls off. The outline circuit arrangement is shown in Fig. 79, standard junction signalling facilities being provided.

Noise Elimination. It will be noticed that junction line and cord circuits are equipped with transmission bridges utilizing four-winding transformers, or 'repeating coils.' By this means, superior balance between A- and B-lines and earth is obtained, since the coils may be more accurately balanced than a pair of relays. As a result, there is less likelihood of induced noise or cross-talk occurring on junction calls.

Jack-ended Trunk Circuits. Some special facilities are required on junctions from trunk exchanges, and a different cord circuit is employed to cater for them. The answering side of the cord circuit (Fig. 80) is adapted to receive supervisory

signals from trunk lines (seventeen-cycle ringing) when plugged into an incoming trunk line jack (5 000-ohm sleeve resistance) the L-relay operating to the alternating current by virtue of the rectifier, and locking via the speaking key until the operator answers. Relays *HR* and *HA* are not operated, and consequently the answering supervisory lamp is flashed from the intermittent earth supply.

When the cord circuit is used to answer a junction call, relays *HR* and *HA* operate, and *LA* controls the supervisory lamp in the normal way.

On the calling side, if the plug is inserted into a subscriber's jack, relays *HJ* and *HC* operate, placing the calling supervisory lamp under the control of relay *LC*, which at *LC*1 controls *SL*. *SL* operates, therefore, when the called subscriber is on the line, and also as long as the speaking key is thrown. *SL*1 removes the anti-singing impedance from the circuit, since a suitable load is now on the line, and *SL*2 completes the through signalling if a junction is connected.

If the calling plug is inserted in an outgoing trunk jack, *HC* only will operate, and *SL* will be permanently energized. The only supervisory signals now received are via relay *L*, and the operator may be recalled by ringing on the circuit.

The resistances across the sleeve relays absorb the induced voltages on breaking the sleeve circuit, and prevent shocks being given to the operator.

Incoming and Outgoing Circuits. The junctions to and from the trunk exchange may be worked on an automatic signalling basis if the resistance of the line conductors permits. In this case, ordinary jack-ended junction equipments are used, and the cord circuit sleeve relays operate to provide the correct conditions. Where automatic signalling is found to be impracticable, generator signalling is employed. The terminating circuits are shown in Fig. 80. On the incoming trunk, a 5 000-ohm sleeve relay is used, thereby preventing the operation of *HR* in the cord circuit. When a ring is received, *L* operates by virtue of the rectifier and energizes *LL*, which locks via *LL*1 until the operator answers. *S* is then energized, and removes the line relay, which is shunted with 600 ohms to provide an anti-singing impedance for any repeater which may be in circuit. The calling lamp is extinguished at *LL*1, and the

call proceeds without further connection with the calling equipment.

The outgoing trunk lines are normally terminated by an

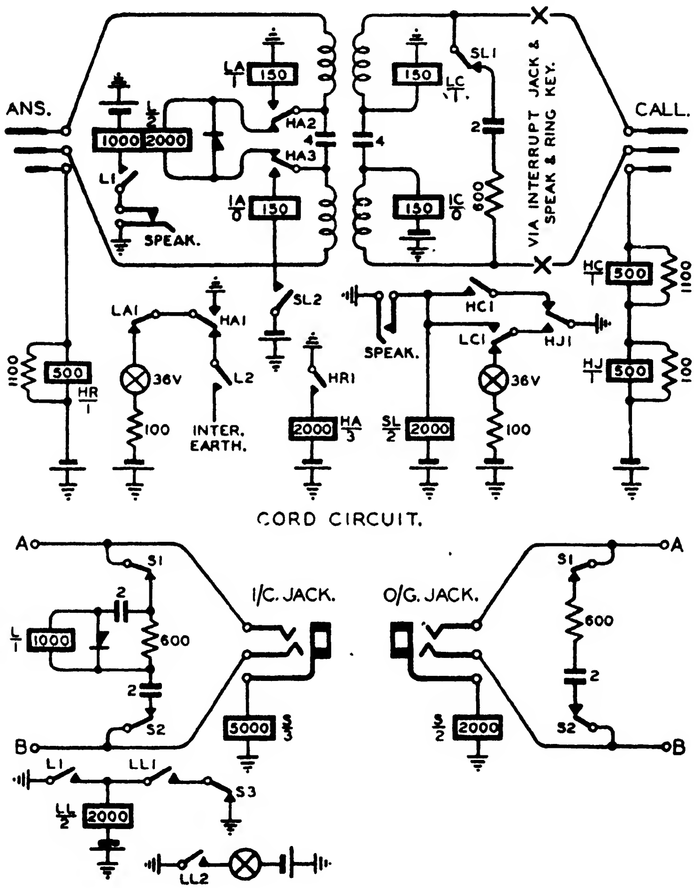


FIG. 80. JACK-ENDED TRUNKS—LINE AND CORD CIRCUITS AT 40-VOLT C.B. EXCHANGES

(a) *HR* operates to 2 000 ohms earth (incoming junction).
HR does not operate to 5 000 ohms earth (incoming trunks).
(b) *HC* operates to 50 ohms or 2 000 ohms earth (subscriber or outgoing trunk or junction).
(c) *HJ* operates only to 50 ohms earth (subscriber or outgoing junction).

'anti-singing' impedance, which is removed by the operation of *S* (2 000 ohms to prevent the energization of *HJ* in the cord circuit). As with the incoming circuit, there is no series or

shunt impedance to cause transmission loss, all signalling being conducted from the cord circuit.

Trunk Interrupt Plug. The jack-ended trunk and jack-ended junction cord circuits are often fitted with interrupt break jacks in the calling side, to facilitate the interruption of a local call when one of the parties is required for a trunk connection. An interrupt plug is fitted on the position, wired as shown in Fig. 81. When the B-operator answers a call from a trunk

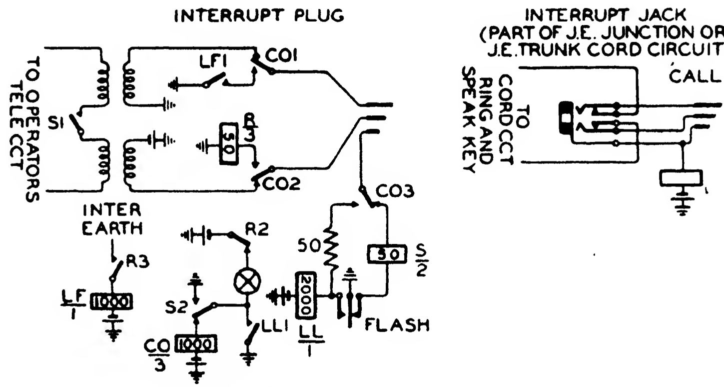


FIG. 81. TRUNK INTERRUPT PLUG CIRCUIT

exchange, and the required subscriber's line tests engaged, the B-operator may be requested to interrupt the call. The interrupt plug is then inserted into the particular cord circuit jack, and the engaged test is again made before inserting the cord circuit calling plug into the subscriber's multiple jack. As *CO* relay is not operated, the 'click' test circuit is completed to the primary winding of a transformer, the secondary of which is joined across the operator's circuit by *S*1, since *S* operates to the battery on the sleeve of the calling plug. If the line still tests engaged, the calling plug is inserted, and the B-operator is now in communication with the conversing parties via *CO*1, *CO*2, and the transformer. The required subscriber is asked whether he will accept the trunk call, and, if so, is requested to replace his receiver until rung. The B-operator now operates the flash key (non-locking), thereby releasing *S*, energizing *LL*, and operating *CO*, which remains energized, since *LL* holds in parallel with the sleeve circuit. *R* operates

to the battery fed out from the cord circuit used in setting up the interrupted call, and at $R3$ connects interrupted earth to the LF relay. $LF1$ earths the tip wire at 0·75 sec. intervals, and thereby short-circuits the supervisory relay of the plug still associated with the interrupted connection. The operator in another part of the exchange who set up the original call, receives the flash, and takes down the connection. As soon as she does so, R releases, and cuts off the flash, and the supervisory lamp glows. The B-operator now withdraws the interrupt plug, and rings the subscriber by means of the ringing key in the cord circuit.

Order Wire Junctions. The operation of the keys by the B-operator on a plug-ended signal position takes an appreciable time and where groups of junctions are sufficiently large, one extra circuit per group is provided, and is used as an 'order wire' between the two exchanges. The A-operator, instead of testing for a disengaged junction to the distant exchange, depresses a non-locking order wire key on the keyboard, which cuts off her telephone circuit from any pair of cords to which she may be connected, and puts her into direct communication with the distant B-operator, whose telephone circuit is connected permanently across the incoming end of the order wire. (See Fig. 82.)

Each A-operator at the outgoing exchange must have access to the same order wire, which is, therefore, commoned to a key on each A-position, the key bearing the code of the junction route which it controls.

Each junction route will have its particular order wire, and there may be as many as eighty of these appearing on each A-position.

The junction circuit at the outgoing end consists merely of the multiple jack with a sleeve resistance of appropriate value to suit the A-cord circuit. At the incoming B-position, the junctions terminate on plugs in front of the B-operator, and one supervisory lamp per cord is provided.

The A-operator, after depressing the order wire key, passes particulars of the number required to the B-operator, who 'allots' a disengaged junction, and at the same time picks up the corresponding plug and tests the multiple jack of the subscriber's line required. Meanwhile, the A-operator at the

distant exchange finds the allotted junction in the outgoing multiple, and plugs in with the calling plug of the pair taken into use in answering the original call. The order wire key is

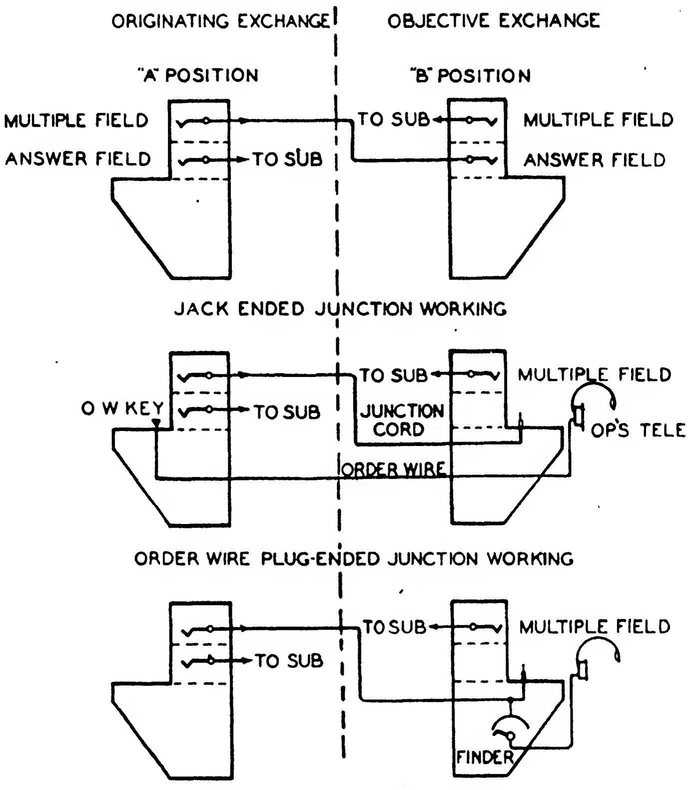


FIG. 82. METHODS OF WORKING MANUAL-MANUAL JUNCTIONS

then released, allowing the A- and B-operators to attend to other calls.

Ringing of the called subscriber from the B-board is automatic, and a supervisory signal is transmitted back to the A-cord circuit when the call is answered. When the called subscriber clears, the signal is given only to the A-operator, who meters the call, providing the calling party has cleared, and withdraws the plug from the outgoing multiple. The removal of this plug gives a clearing signal to the B-operator, who takes down her connection.

The saving of both operators' time in this method of working is considerable, but the main disadvantage is the interference caused by more than one A-operator seizing the order wire at once. Where there are insufficient junctions in a route to provide one B-operator with a full load, two or more junction routes are terminated on one position, and the order wire to

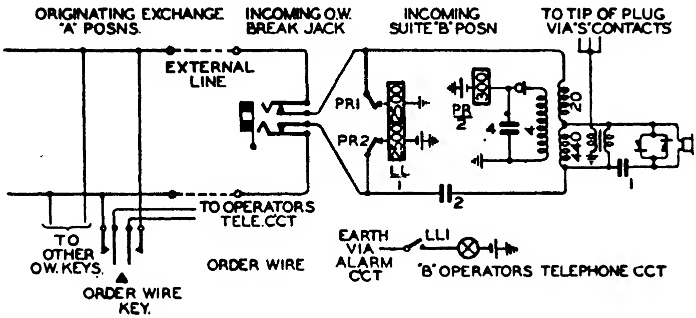


FIG. 83. B-OPERATOR'S TELEPHONE CIRCUIT WITH ORDER WIRE CONNECTIONS

the B-operator is 'split' between the various originating exchanges.

Straightforward junction working overcomes these drawbacks, whilst retaining the main features of the order-wire controlled plug-ended automatic ringing junctions.

B-Operator's Telephone Circuit (Fig. 83). This is similar to that used for A-positions, except that an additional transformer is used to enable the engaged test to be received, and relays are added to the circuit to provide signalling facilities on the incoming order wires when the position is not staffed.

The tip conductors of all the cords on the B-position are taken via the contacts of the individual sleeve relays to a common point, whence they are connected to one terminal of a transformer primary winding, the other being earthed. The secondary winding is connected across the receiver circuit and, therefore, if the tip of any plug is tapped on to the bush of an engaged jack, a small current will flow in the transformer primary, which will result in a 'click' in the operator's receiver. As each cord is taken into use, its tip conductor is disconnected from the common, to prevent interference between different circuits.

The impedance coil in series with the transmitter in the A-operator's circuit is replaced by a relay of similar resistance. Break contacts on the relay (PR) place a second relay *LL* across the incoming order wire and the relay will operate to a loop on the order wire from the outgoing end if the B-operator has withdrawn the telephone plug. Contacts of relay *LL* light

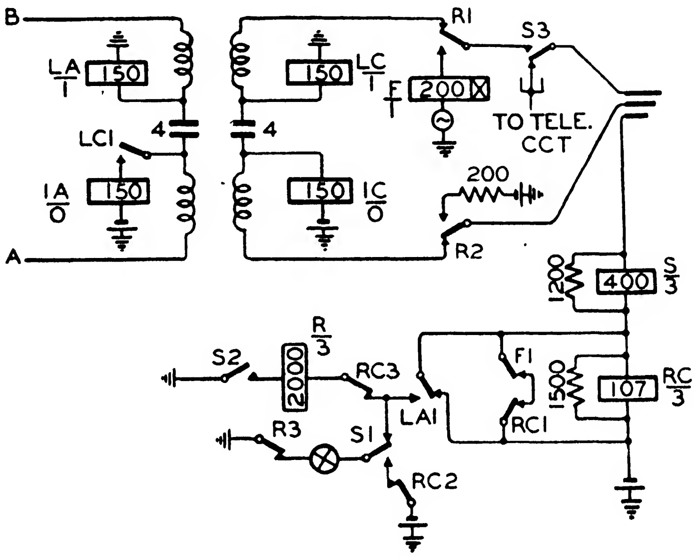


FIG. 84. INCOMING ORDER WIRE JUNCTION
C.B. 40-volt system.

the pilot lamp and actuate the night alarm. If the B-operator desires to speak over an outgoing order wire, the order wire key is arranged to operate a relay, which disconnects the incoming order wire (or order wires) from the telephone circuit, and connects them to a tone supply, thereby informing distant A-operators that the order wire is momentarily disconnected.

Incoming Order-wire Junction. The circuit used at a 40-volt exchange is shown in Fig. 84 and at a 22-volt exchange in Fig. 85. The circuit principles are similar, and only the former will be described. The outgoing jack connections are shown in Fig. 86.

After the B-operator has received the demand from the distant A-operator over the order wire, the tip of the plug of

the particular junction allotted is tapped on to the sleeve of the required subscriber's multiple jack. If engaged, the battery potential on the sleeve will cause a flow of current via $S3$ to the transformer winding in the B-operator's telephone circuit (*q.v.*)

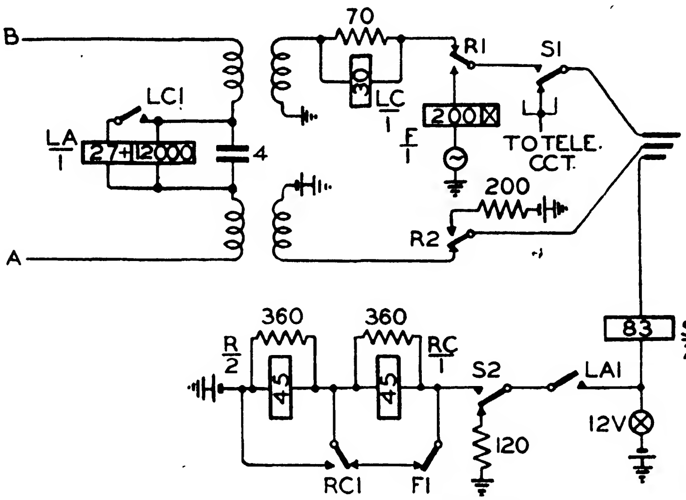


FIG. 85. INCOMING ORDER WIRE JUNCTION
C.B. 22-volt system.

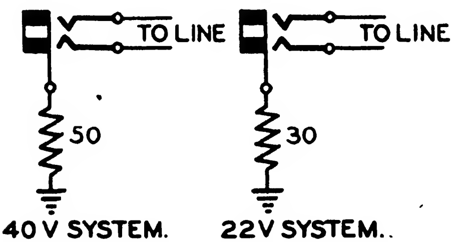


FIG. 86. OUTGOING ORDER WIRE JUNCTION

giving the engaged 'click.' The junction plug is thereupon inserted into a busy-back jack, to advise the distant A-operator of the condition.

If the jack tests free, the plug is inserted, and S operates, removing the tip conductor from the test common and causing the supervisory lamp to glow at $S1$. When the A-operator picks up the junction at the outgoing end, LA operates and energizes R, which connects ringing current to the subscriber's

line at $R1$ and $R2$, dimming the supervisory lamp at $R3$. When the called subscriber answers, F operates on the increased current flowing to line, and removes the short circuit from RC, which then operates in series with S. R is de-energized at $RC3$ and the caller is put through to the called subscriber via the transmission bridge, which affords through signalling facilities at $LC1$. If the called party should clear prematurely he may be re-rung by the A-operator by a momentary withdrawal of the

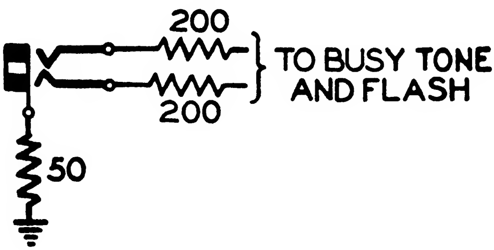


Fig. 87. Busy-back Jack

calling plug, thereby short-circuiting $RC3$ at $LA1$, and setting up ringing conditions once more. The B-operator's cord circuit supervisory lamp does not glow until the A-operator clears and releases LA. RC restores, R cannot reoperate, and the B-operator takes down the connection, the release of S dimming the supervisory lamp and restoring the circuit to normal.

If desired, ring-back tone may be given to the calling party by connection of a 0·02 μF. condenser across the break of $R1$, thus feeding back a portion of the ringing current to the transmission bridge. Should the number asked for be temporarily out of service for any reason, the B-operator will pick up the 400 cycle tone (applied to the bush of the jack by a plugging up cord circuit) on making the engaged test, and will then route the call over a transfer circuit to the testing telephonist's position at the end of the A-suite, where the caller will be advised of the particular circumstances.

Busy Conditions. If an A-operator tests a line and finds it engaged the caller is informed of the fact, and replaces his receiver. When a B-operator makes the test, however, there is no means of informing the caller that the line is engaged, if the call has been passed over an order-wire junction. The junction plug is therefore inserted into a busy-back jack, wired as

shown in Fig. 87. Busy tone and flash is fed out on the tip of the jack, and this results in transmission of the tone to the subscriber, as well as the flashing of the supervisory lamp in the A-cord circuit. The A-operator clears the connection when the subscriber has replaced the receiver, and the B-operator thereupon receives a clear on the junction supervisory lamp.

Junctions between Manual and Automatic Exchanges. Calls from manual subscribers to subscribers on an adjacent auto-

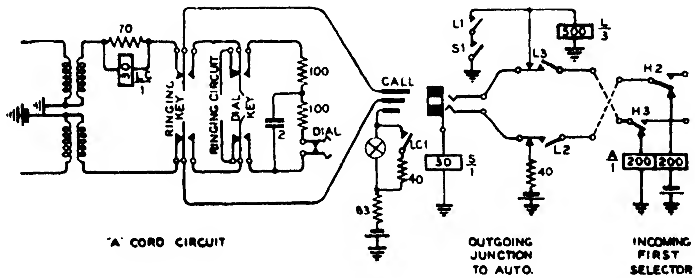


FIG. 88. LOOP DIALLING FROM 22-VOLT C.B. EXCHANGE

matic exchange may be completed by the A-operator at the manual exchange, by providing a dial on the A-position and terminating the junction by a selector at the automatic exchange.

Loop dialling facilities to the automatic switches can be given only if the manual exchange has 22-volt equipment. This is due to the fact that in the through connection, after the ringing and dialling key has been restored (see Fig. 88), the A-position cord circuit must hold the final selector. The earthed tip is through to the earthed side of the final selector A-relay and the battery on the ring is extended to the battery connected coil. Unless the difference in exchange voltages is sufficient to permit enough current to flow to hold the A-relay on one winding, the selectors will release. When the called subscriber answers, the polarity is reversed, and the holding is over both lines, with each exchange battery connected to earth at the distant end. If, with 22-volt C.B. equipment, the junction resistance exceeds 280 ohms loop, the holding current will be insufficient, and other means must be adopted.

With the loop dialling scheme, the dial is associated with the A-position ringing circuit by means of an additional key.

and during dialling this key must be operated, and the ringing key must be held over.

The chief difficulty is the danger of false impulses being received on the distant selector during the insertion of the

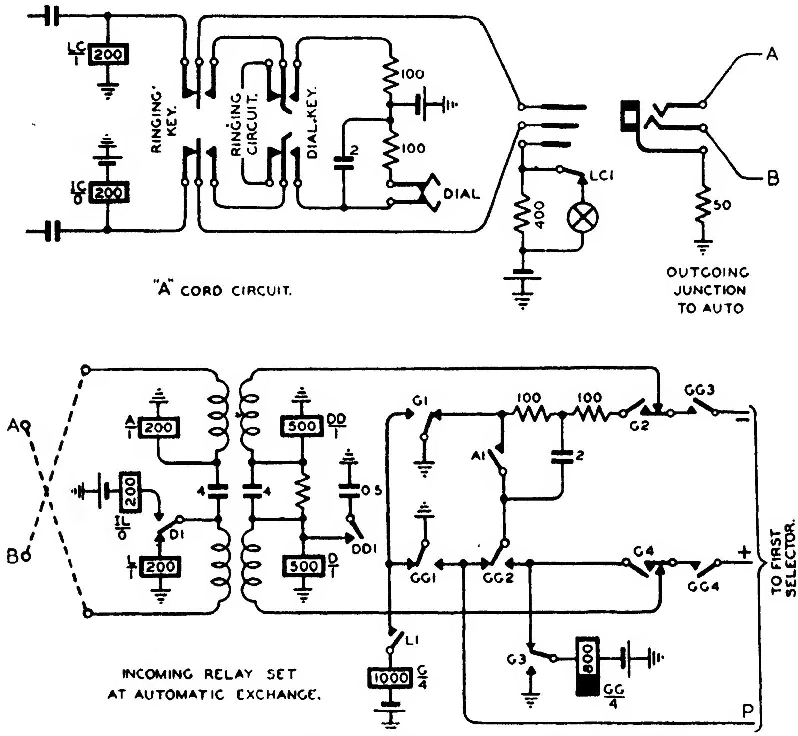


FIG. 89. BATTERY DIALLING FROM 40-VOLT C.B. EXCHANGE

calling plug in the outgoing junction jack. The tip of the plug is earthed, and engages momentarily with the ring spring of the jack, thereby impulsing the distant selector over the negative line. Such false impulses are avoided, in the circuit shown, by introducing an additional relay *L* in the outgoing circuit, which relay can only be operated when the loop of the dialling circuit has been placed across the tip and ring conductors. The junction lines are then extended through to the dial, and impulsing may commence.

Junctions from 40-volt C.B. exchanges, and from 22-volt

exchanges where the junction resistance exceeds 280 ohms loop, are worked on a battery dialling basis.

No additional equipment is employed at the outgoing end, where conditions are normal, except that battery is connected to the dialling circuit, but the incoming end of the junction is terminated on a relay set, which receives the battery impulses from the dial, and converts them into loop impulses to the selectors.

The circuit is shown in Fig. 89, and the operation is as follows.

Battery Dialling Relay Set (Incoming). Distant A-operator inserts plug in outgoing jack. Relay *A* operates to battery from the ring of the cord circuit. *A*1 earths private to engage outgoing portion if circuit is bothway. Dial tone is not provided, as an individual selector is allotted. The operator now throws the dial switching key, and then holds over the ringing key. The battery from the dialling circuit is now extended to the tip and ring of the plug, thereby retaining *A* operated, and energizing *L*.

*L*1 operates *G*, *G* holds via *G*1, whilst *GG* is operated at *G*3.

With relays *G* and *GG* operated, the incoming first selector is extended to a loop containing the *A*1 contact.

During dialling, *A* impulses to the interrupted battery from the ring, whilst *L* is retained.

*A*1 steps the train of selectors.

After the last digit has been sent out, the operator restores the keys to normal.

L releases, but *A* is maintained.

G releases at *L*1, but *GG* is held via *G*1 restored.

DD operates to the battery from the final selector A-relay, the 0·5 μF. condenser being connected at *DD*1 to ensure the transmission of ring-back tone, since *D* and *DD* are high impedance relays.

When the called subscriber answers, the final selector battery is transferred to the other line, *DD* releases and *D* operates. *D*1 replaces the earthed relay *L* by battery through the impedance *IL*, which actuates the supervisory relay in the manual exchange cord circuit.

If the called subscriber is engaged, *D* will flash to the busy signal, and flash and tone will be relayed to the A-cord circuit.

The release of relay *A* on withdrawal of the calling plug releases *GG* and the selector train.

Calls Outgoing from Automatic to Manual. Junctions to adjacent manual exchanges are generally terminated on the banks of second selectors at the automatic exchange, and it is necessary to insert a relay set in the outgoing line so as to

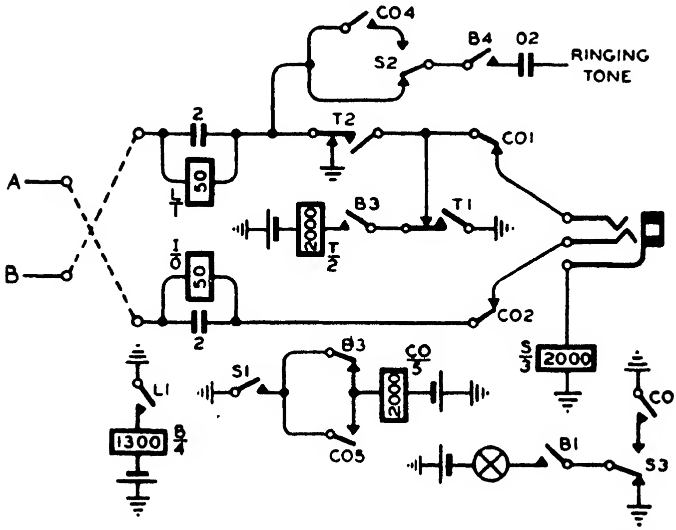


FIG. 90. INCOMING JUNCTION WITH 'FOLLOW-ON' CALL FACILITY

provide holding and metering conditions, and a transmission bridge for feeding current to the calling subscriber.

At the incoming manual end, another relay set is installed, which supplies ring-back tone, arranges for the lighting of the calling lamp, and gives the facility of receiving a 'follow on' call; i.e. when the junction is cleared at the automatic exchange before the operator has withdrawn the plug, the junction tests free to calling subscribers, and will again be picked up. The calling lamp then glows again, but connection to the original called party is prevented.

The circuit is shown in Fig. 90, and is answered at the incoming end by the answering plug of a jack-ended junction cord circuit (*q.v.*).

Outgoing to Manual Relay Set (Fig. 91). The calling subscriber or operator dials the relevant code, and the group

selector switches to a disengaged relay set. L operates, $L1$ operates J, and $L2$ operates HJ. The private is guarded at $HJ1$. $HJ2$ and 3 disconnect the incoming equipment if the circuit is bothway, and extend the wet loop (relay D and impedance CL) to call the manual exchange.

Relay L in the incoming termination operates to battery

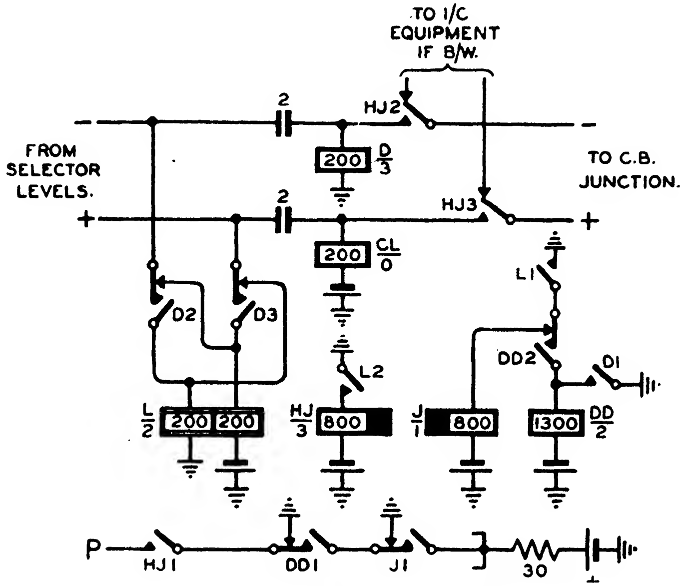


FIG. 91. OUTGOING RELAY SET: AUTOMATIC TO C.B.

from CL, and $L1$ energizes B. $B1$ lights the calling lamp and $B4$ connects ringing tone.

S operates when the B-operator answers. $S3$ disconnects the calling signal, and $S2$ the ringing tone. T is energized from earth on the tip of the plug via $B3$, and holds via $T1$, thereby extending the caller to the operator.

J.E.J. cord circuits which are employed to answer calls from automatic exchanges are arranged not to return a supervisory battery signal on the ring of the answering plug when the operator answers. This avoids premature metering if the called subscriber is engaged or unobtainable.

When the called party answers, the through signal is given back to the automatic exchange, and D operates, $D1$ energizing

DD, which holds via *DD*2. *D*2 and *D*3 reverse the polarity of the lines for supervisory purposes, and *DD*1 applies the metering pulse during the slow release of *J* from *DD*2. The circuit is cleared from the release of *L*, 'manual hold' not being provided.

Should the manual connection not be cleared until after the automatic selectors release, *CO* in the manual termination operates via *S*1 and *B*3. If now a 'follow on' call is received, the calling lamp again glows, this time via *CO*3 and *B*1, and ringing tone is extended over *B*4, *S*2, and *CO*4, but the speaking circuit is not joined through.

The manual operator, observing the lamp glow, withdraws the plug, releasing *S* and restoring calling conditions to normal. Reinsertion of the plug allows the call to be completed as before.

Other Circuits. Calls to and from trunk and toll switchboards and automatic exchanges are dealt with under 'Trunk Working,' as the different type of equipment on the switchboards necessitates a change in the circuits involved.

Straightforward Junction System. 'Straightforward' junctions supersede order wire junctions and signal junctions in most cases where the traffic between two exchanges warrants the provision of unidirectional circuits. In this system, the A-operator selects (by the engaged test) a free junction to the distant exchange, and listens for a 'pip-pip' tone signal, which indicates that a B-operator has been connected by automatic switching to the incoming termination. Particulars of the call are then passed by the A-operator, and the B-operator completes the connection by plugging into the multiple.

This operation dissociates her telephone circuit from the junction, and prepares it for use on further calls.

There are two methods of working straightforward junctions —with or without distribution over the whole suite of B-positions.

Non-Distribution Scheme (Fig. 92). The junctions from distant exchanges are terminated on individual cords on the incoming B-positions, a maximum of thirty-six being accommodated on each position.

The B-operator is connected to any one of the thirty-six cords on her position by means of a pair of uniselectors termed

cord circuit finders. The eighteen cords to the left of the position are connected to the bank contacts of one of the twenty-five point switches, and the eighteen cords to the right, to the bank contacts of the second switch. Discriminating relays in the position circuit are used to determine on which bank a particular incoming call may be picked up.

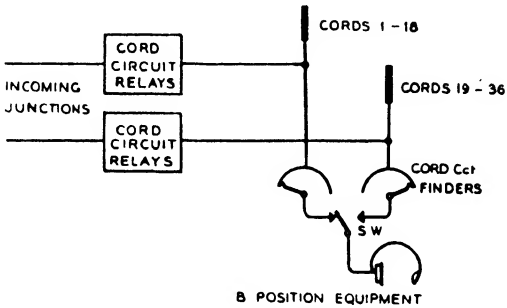


FIG. 92. S.F.J. WORKING—UNCOUPLED POSITION WITHOUT DISTRIBUTION

Normally, on each B-position, the wipers of the switches are connected through to an idle cord, but when the distant A-operator plugs into a junction terminated on any one position, the cord circuit finders on that position step quickly to the relevant contact, and connect the B-operator across the tip and ring of the plug. At this instant the 'pip-pip' signal is automatically sent out to the A-operator, who passes the demand over the junction, and the B-operator, after making the engaged test, inserts the plug into an outgoing junction or subscriber's multiple jack, thereby freeing her telephone circuit for connection to the next call.

Distribution Scheme (Figs. 93 and 94). Where a large number of incoming junctions exist, comprising groups from several exchanges, economies in B-position staffing can be effected by arranging for the even distribution of incoming calls over all staffed positions. In the busy hour, all positions will be staffed, and calls are dealt out to the operators in rotation, but during slack periods, positions may be closed down, and the withdrawal of any B-operator's head-set plug from the jack is arranged to busy automatically all cord circuits connected to that position. In the extreme case, therefore, when only one

position is staffed, all incoming calls are diverted to cords on that position.

The switching scheme used is somewhat complex, and complete flexibility is not given, but the grade of service obtained is satisfactory.

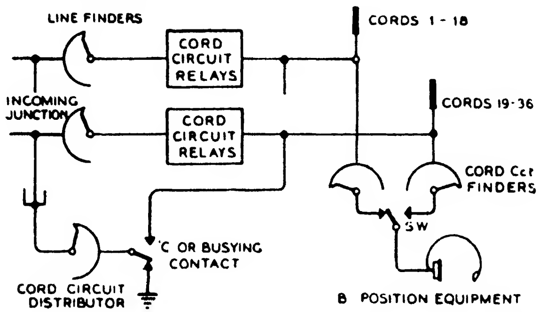


FIG. 93. S.F.J. WORKING—UNCOUPLED POSITION WITH DISTRIBUTION

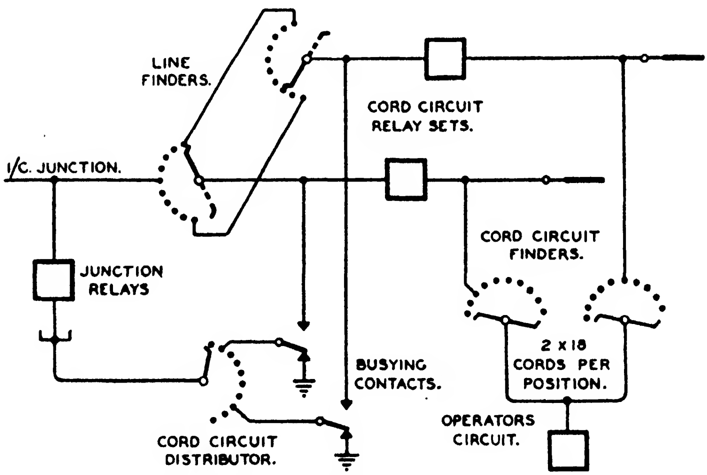


FIG. 94. MANUAL STRAIGHTFORWARD JUNCTION WITH DISTRIBUTION

The incoming junctions are terminated on the banks of 50-point line-finders, utilizing ordinary uniselector mechanisms, which are cross-connected to the cord circuits in such a way that each junction group (up to fifty junctions) is accessible from one or more cords on each position. Thus, no matter in which group a call originates, an outlet will exist to any position which may be staffed, provided a previous call in the same

group has not been dealt with on the same position. This is safeguarded against by distributing the incoming junctions over the contacts of the various groups of 50-line finder banks in such a way that even with the lightest traffic load each junction group is evenly loaded. The schedule (Fig. 95) shows one method of achieving this result, thereby greatly decreasing the probability of two or more simultaneous calls in one group

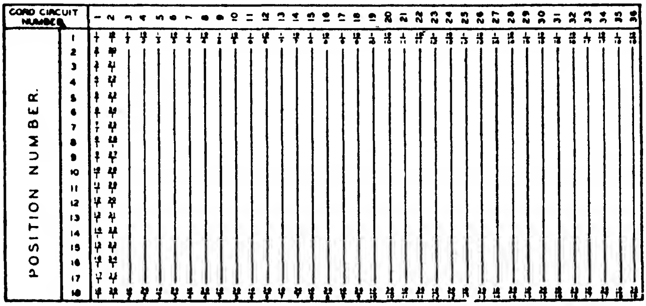


Fig. 95. S.J.F. System—Cross Connections between Line-finders and Cord Circuits

Example showing 18 positions equipped with 36 cords each, served from 18 groups of line finders.
Note. 18/8, etc., indicates finder 18, group 8.

when the traffic is light enough to warrant opening only one 'B' position.

As positions are brought back into use, the reinsertion of the B-operator's telephone plug removes the busy condition from the cords, and more outlets to incoming calls are made available. Suitable alarm signals are given if congestion occurs, and the supervisor is warned of the necessity for staffing more positions. The cross-connection diagram (Fig. 96) indicates how the cords are connected to the line finders to ensure the maximum availability of outlets under all conditions of loading.

A cord circuit distributor, associated with each group of junctions, selects a free cord circuit connected to a staffed position each time a call comes into the group.

The bank contacts of the distributor switches are busied by the release of the position relay of the particular position to which they may be cross connected, and also by the insertion of a special plug into the busying jack. One such jack is provided per cord circuit, and the operator or maintenance

officer may put circuits out of use which are suspected of being faulty.

Arrangements are made whereby incoming calls are only connected to staffed positions at which the B-operator is not at the moment engaged in completing a call.

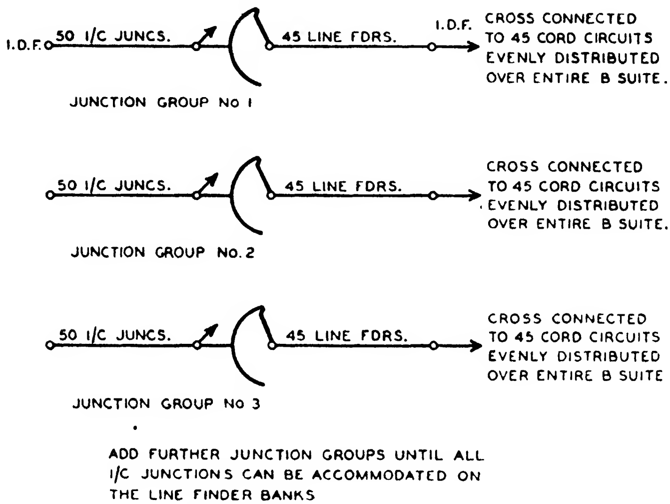


FIG. 96. CROSS CONNECTIONS OF S.F. JUNCTIONS AND CORDS

This is effected by releasing all the busying relays connected to a position during the time taken by the B-operator in completing a call. The effect is as though the telephone plug were momentarily withdrawn, and all outlets to that position are marked busy until the call is completed in the multiple.

Under congestion conditions, when the operators at all staffed positions may be simultaneously engaged, a master relay operates, re-energizing the whole of the busying relays on staffed positions, and allowing calls to be distributed to them on a pure chance basis.

General Facilities. Straightforward junctions give standard supervisory conditions to the distant A-operators, with automatic ringing as on order wire junctions. On junctions from trunk exchanges, trunk offering facilities and operator control of ringing can be provided.

The B-operator is dependent on the junction supervisory lamp (fitted in front of each cord, on the keyshelf) to indicate

the state of the call. When an A-operator plugs in the outgoing multiple jack, the relevant lamp on the incoming B-position glows steadily.

As soon as the junction is picked up by the cord circuit finders, the lamp flashes 0·2 sec. on and 0·2 sec. off, warning the B-operator that the connection is through. At this stage the 'pip-pip' tone is sent out, and if the A-operator does not pass the demand within a reasonable time, or if the junction has been seized due to a fault occurring on the external line, the B-operator depresses a junction release key on the position. This key cuts the B-operator off from the particular cord, holding the latter engaged until the call is cleared.

On insertion of the cord circuit plug into a multiple jack by the B-operator, the lamp is darkened, and does not again glow until the originating operator clears the connection.

Should the B-operator be slow in withdrawing the plug, a 'follow on' call may be received on the same cord. In this case, the supervisory lamp flashes, and the subscriber already connected is not re-rung, neither does that particular line test engaged to any other B-operator. This is achieved by inserting a high resistance in the sleeve circuit on clearing, and reducing the potential at the B-multiple jack to about 0·06 volt. The plug is withdrawn and inserted into the jack of the line next demanded.

If the B-operator gets the engaged test click on testing a multiple jack, she depresses the position busy key, which clears her telephone off the cord in use, and connects busy tone and flash to the latter until such time as the distant operator clears.

Position Coupling (Fig. 97). With either the distribution or non-distribution scheme, arrangements can be made for automatic coupling of adjacent positions during non-busy-hour conditions of staffing.

The positions may be coupled in groups of six as a maximum, and in every large S.F.J. installation at least one such coupled group is provided. By this means the number of cord outlets from individual junction groups when only one position of a coupled suite of six positions is staffed is six times greater than in the case when one uncoupled position is staffed, even though only one operator is needed in each case. It is not necessary for the whole B-suite to have interposition coupling facilities,

since after about 30 per cent of the positions are in use on a coupled basis, the availability of free cords from the individual junction groups is quite good, and the staffing of single positions

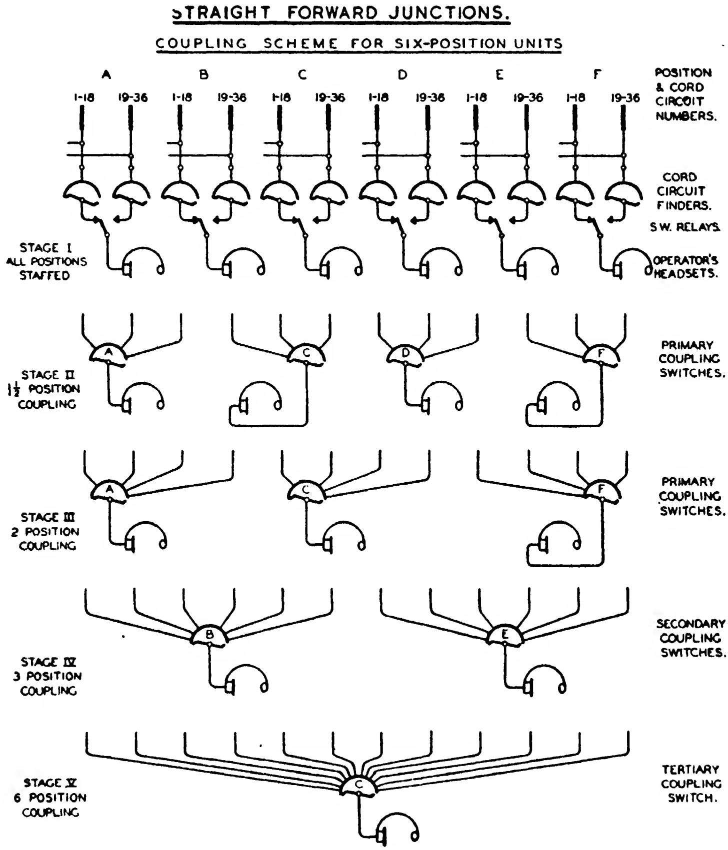


FIG. 97. S.F.J. POSITION COUPLING

results in the operators obtaining a correct proportion of the total load on the exchange.

The coupling is effected automatically by withdrawal of the operator's telephone plug, and is completed in stages, as shown in the schematic diagram (Fig. 97). The advantage in providing two cord circuit finders per position is now clear, since half a position may be coupled on either side of a staffed one.

In the event of an incoming call being unable to find a free outlet to a group of coupled positions, a *position opening distributor* comes into use, and opens up adjacent positions on which outlets are available. The choice of position to be opened is governed by the stage of coupling in use, and is arranged to suit most conveniently the particular staffing arrangement existing at the moment of congestion.

If a fault occurs on a particular coupling switch, it may be overcome by a rearrangement of the staff, thus utilizing a different coupling scheme until the defect can be remedied.

Group Engaged Test (Fig. 98). At the outgoing end of each S.F.J. route, the O.G.J. multiple is divided up into groups of five junctions on consecutive jacks, the first having a characteristic marking. Sleeve relays are used to connect a tone to the first jack if all five are engaged, thus saving nearly four-fifths of the operator's time in making the engaged test on a large group. In the absence of tone on the marked jack, the individual jacks in the group of five are tested for the usual 'click.' The circuit is self-explanatory, and with large groups, A-operators on different positions may be instructed to commence testing at different points in the group, so as to reduce the overall testing time when most of the junctions are engaged.

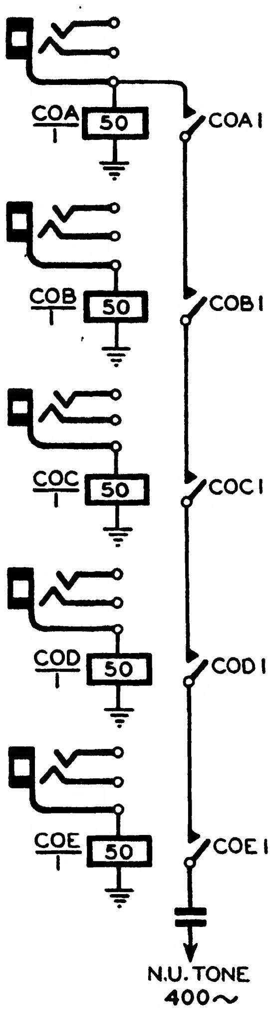


FIG. 98. SET OF FIVE CONSECUTIVE MULTIPLE JACKS WITH GROUP-ENGAGED TEST

CHAPTER VI

MANUAL EXCHANGE EQUIPMENT

General Arrangement of Switchboards. At manual C.B. exchanges, two types of operators' positions are provided in the main suites.

A-positions cater for the subscribers' originated traffic, and B-positions for incoming junction traffic. The two types of positions are retained in separate groups, though in the smaller exchanges the groups may be in one common suite. In such cases, the positions near the junction of the two groups are equipped for mixed A- and B-traffic, so as to permit operating flexibility when the exchange is not fully staffed.

A suite of positions commences with a Cable Turning Section (C.T.S.), in which the multiple and answering jack cables are turned from the cable rack into the horizontal multiple shelves or runways in the switchboard. The construction of the iron-work supporting the cables in the C.T.S. is such as to allow the multiple over the first position to be raised for maintenance purposes when desired. The C.T.S. also serves to accommodate the various keys for night alarms, concentration, delay working, etc., and in some cases also the position meters.

The face of the switchboard is divided into vertical panels, each of sufficient width to accommodate one strip of jacks and one 'style-strip' for designation purposes. Each operator's position occupies 1 ft. 11 in. in the older switchboards, and 2 ft. 3 in. in more modern equipment, and for convenience in erection the board is supplied in either single, two, or three-position sections. The number of panels to a three-position section is seven, eight, or nine, depending on the width of the position and the gauge of the multiple jack used. (The latter determines the length of individual strips of jacks, and consequently the width of each panel.)

A single position may be served by two or three panels, and a two-position section by four or six.

The standard arrangements for exchanges are—

*C.B.*1 *exchanges.* Three-position sections with 1 ft. 11 in. positions and eight panels per section (small gauge jacks).

*C.B.*10 *exchanges.* Single 1 ft. 11 in. positions, with two panels per position (large gauge jacks).

Trunk and Auto-manual exchanges. 2 ft. 3 in. positions, with seven panels per three positions section (large gauge jacks).

The lower portion of each panel is reserved for the subscribers' answering jacks and lamps on A-positions, and for incoming junction calling equipments.

J.E. B-positions. The equipment may be ancillaried over other positions if desired. The loading of the various panels is controlled by the cross-connections on the I.D.F.

Below the lowest jack strip the various pilot and miscellaneous lamps are fitted, with suitable colour codes to indicate the relevant service.

Above the answering jacks is the outgoing junction multiple (O.J.M.), which is completely repeated every four or six panels, so as to give each operator easy access to the whole of the outgoing junctions. The remainder of the space above the O.J.M. is occupied by the subscribers' multiple, repeated every eight or nine panels.

Ordinary A- and J.E. B-positions are equipped with seventeen pairs of cords, some of which may be modified for dealing with coin box calls. The hinged keyboard accommodates the ringing and speaking, order wire, and meter keys. The telephone circuit jack is provided in duplicate in the lock rail, so that an operator may be relieved without interruption to the service.

The J.E. B-positions commence from the C.T.S. and are followed by ordinary A-positions, since the rate of growth of the J.E. B-positions is considerably lower than that of the A-board, and may more readily be met by connecting A-positions as desired.

A separate B-suite is installed in most cases where incoming order wire or 'straightforward' junctions are provided. The general arrangement of the positions is similar to that described above, but as there is no answering equipment to be accommodated, the O.G.J. and subscribers' multiples are fitted lower in the panels.

The junctions are terminated on single plugs and cords, each position accommodating from thirty-three to forty single circuits. No cord circuit keys are required, but break jacks are

sometimes provided to allow the operator to plug into any junction on which she may desire to speak.

Timing facilities are provided on certain A-position cord

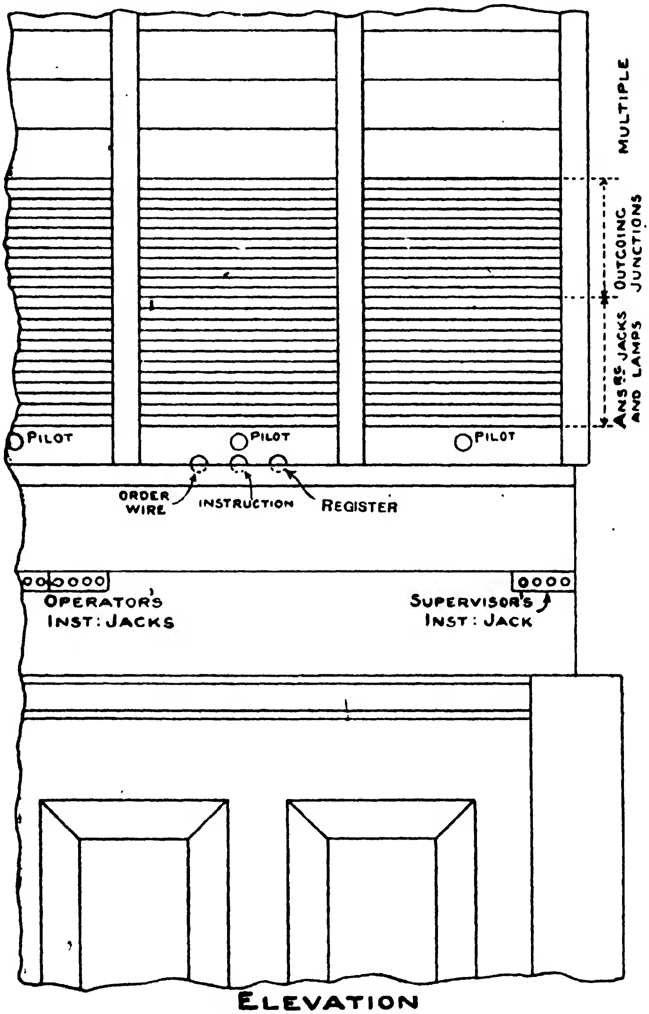


FIG. 99. FRONT OF A-POSITION

circuits if control of toll calls is given to the operators. The arrangements are similar to those described under "Trunk Working."

Fig. 99 is a sketch of part of the front of a typical A-section, and shows the relative positions of the subscriber's multiple, the outgoing junction multiple, and the answering jacks and

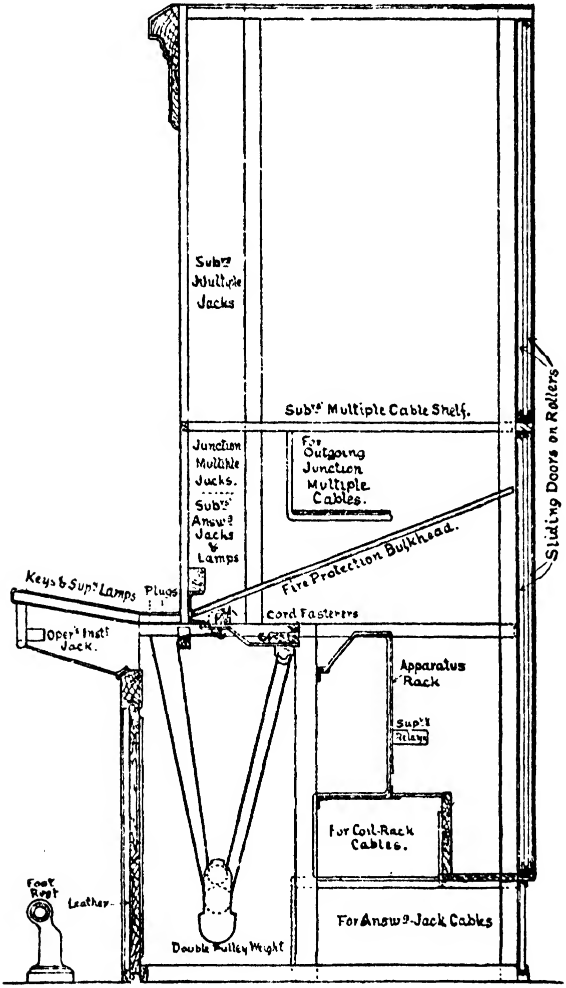


FIG. 100. CROSS-SECTION OF A-POSITION

calling lamps. Fig. 100 shows the same switchboard in cross-section, and indicates the manner in which the connecting cords and cord-circuit apparatus are fitted. The shelf which carries the subscribers' multiple cables is of sheet iron, and is

continuous from back to front of the section and from end to end of the whole suite of sections. The rear shutters are also of iron, so that the upper and lower portions of the section are entirely separated. The sections are also divided at intervals laterally by iron partitions. A uralite screen in removable sections is interposed between the cord fastener shelf and the answering and outgoing junction jacks. Similar precautionary

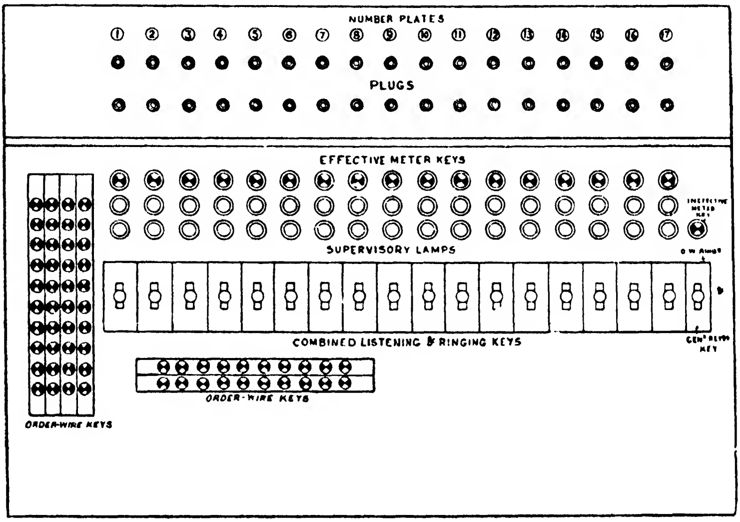


FIG. 101. PLAN OF KEYSHELF

measures are embodied in the construction of the switchboard wherever possible, all with the object of minimizing the risk of fire, and of localizing the damage should it occur.

Plug Shelf. This is a horizontal shelf covered with fibre running the whole length of the section. It is fitted with three groups of seventeen pairs of plugs, one group for each operator's position. In order to obtain the necessary length in the connecting cords to reach any multiple jack, the cords are passed through a special system of pulleys. The action of these will be readily understood from a reference to Fig. 100. The usual length of cord employed is 9 ft. 6 in.

Key Shelf. This is continuous over the whole section, and like the plug shelf is covered with fibre, but is divided into three portions, one for each operator's position. Each portion is

separately hinged on to the plug shelf. The key shelf carries the combined speaking and ringing keys, the meter keys, the order wire keys and the supervisory lamps. Fig. 101 shows a plan of the plug and key shelves for one operator's position.

FIG. 102. OPERATOR'S HEADSET AND BREASTPLATE TRANSMITTER
(*Siemens Bros. & Co. Ltd.*)

The plugs, lamps and keys belonging to each connecting cord circuit are fitted in line from back to front, the rear plug of each pair being the one reserved for answering. The order wire keys are fitted in strips of ten at the side, and in front of the row of combined speaking and ringing keys. Below the keyboard, in the lock rail, is fitted the jack for the operator's

telephone instrument. The headgear receiver and breastplate transmitter are shown in Fig. 102. A view of a complete A-position is given in Fig. 103.

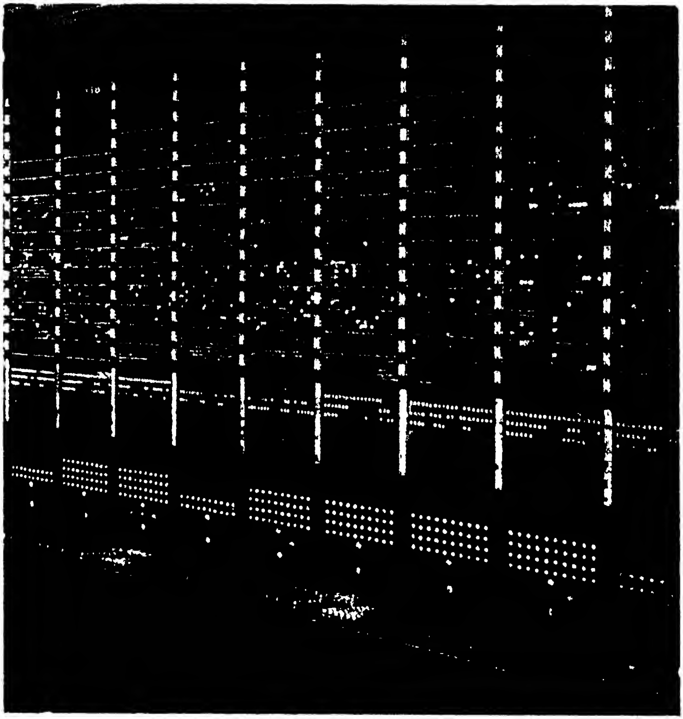


FIG. 103. A-POSITION
Front view.

Jack-Field. The front of the switchboard, where the jacks, calling lamps, etc., are fitted, is called the 'jack-field.' There are eight panels in each switchboard section, and at the bottom of each panel is fitted the pilot lamp, which is lit each time any calling lamp in that panel glows. The 'calling' lamps and 'answering' jacks are fitted at the lower part in alternate rows of ten, the jacks being fitted above the corresponding lamps. Above these again are fitted 'outgoing junction' jacks in rows of ten or twenty, through which jacks connections are made for calls to other exchanges.

The subscribers' 'multiple' jacks are fitted above the out-going

junction jacks in strips of twenty, five strips being grouped together so as to give sets of 100, which are separated from other sets by thin white lines painted in the grooves between the jacks. All such sets of 100 are numbered from 0 to 99, and each set is numbered by a white number plate fitted on the stile strip at the left-hand side of each set. The first of such sets (which usually commence on the left of the first section on the lowest multiple row) is numbered 0, for numbers ranging from 0 to 99. The next set to the right is numbered 1, and is for lines numbered from 100 to 199. The third set is numbered 2, for numbers from 200 to 299, and so on to the ninth set, which is numbered 8, for 800 to 899. The tenth set is fitted over the 0 set, and numbered 9, thus commencing another row of hundreds, numbered from 9 to 17, the latter being fitted over the ninth set, numbered 8, and so on, building upward until the full number of subscribers has been provided for.

As a rule in large towns more calls are completed over the outgoing junction lines than are set up locally on the subscriber's multiple. For this reason the outgoing junction jacks are placed below the subscriber's multiple jacks, thus minimizing the operator's 'reach' on the greater part of the calls handled. For similar reasons the complete multiple of outgoing junction lines is repeated every six panels.

Pilot Lamps. In the centre of each operator's position there are provided three large lamps. The right-hand one is the meter, or register lamp, the centre one is the 'instruction' lamp, and is used to call the operator's attention to an instruction to be given by one of the supervisory officers to one or more of the operators. All the instruction lamps on the switchboard glow simultaneously when the supervising officer calls on the circuit, and each of the operators thereupon presses a special order wire key, and listens to the instruction. The left-hand lamp is called the 'special order wire' lamp. It is intended to call attention to the fact that a special charge is to be made for the call. It glows only when an order wire key is pressed which connects to an exchange situated out of the ordinary territory, and for which call an extra fee is exacted.

The photograph reproduced in Fig. 104 shows a rear view of a subscriber's section. At the top are the subscriber's multiple cables; beneath them are seen the outgoing junction multiple

cables. The subscriber's answering jacks and calling lamps are located behind the fireproof screens through which the cables pass to each panel. The cord fastener shelf is immedi-

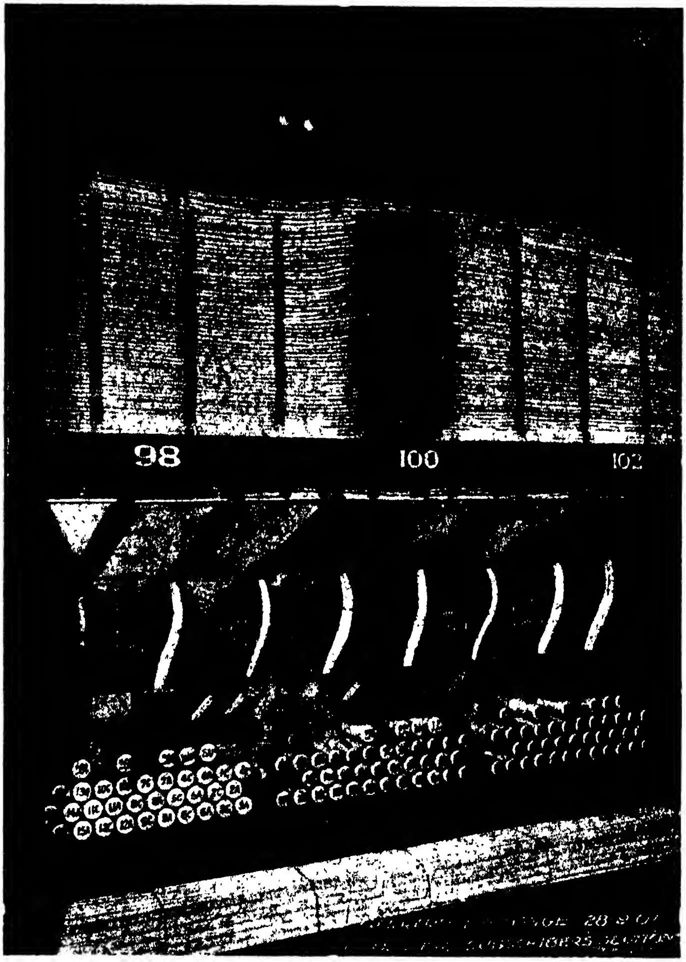


FIG. 104. A-POSITION
Rear view.

ately below the fireproof screens, with the supervisory relays and resistance spools, etc., in front. Beneath the relays are the connecting racks on which connection is made to the repeating coil cables running in front.

Service Markings. Owing to the large variety of services to which subscribers may be entitled, it is necessary to inform the operators which facilities shall or shall not be allowed to each of the subscribers, and also as to when a record of the call should be made on a ticket or a fee demanded.

The opal caps of the calling lamps lend themselves very conveniently for these service markings, as the light behind throws up the markings very distinctly, and no extra space is required for them.

When a subscriber has two or more separate lines to the exchange an endeavour is made, as far as possible, to give consecutive numbers on the switchboard; and in order to inform the operator of the fact a line is painted under the jacks in the multiple section, so that she may connect to another line if one is engaged.

The B-switchboards are very similar in general design to the A-boards just described, but as there are no subscribers' calling signals and answering jacks to be accommodated, the subscriber's multiple is fitted in a lower position. Since all calls received over the junction lines are completed on the subscriber's multiple, the multiple is repeated more frequently than on the A-sections, usually every six panels. This facilitates the rapid handling of calls by reducing the operator's reach. A small outgoing junction multiple is generally provided. The lines on this multiple mostly run to small exchanges, which have no direct lines to other exchanges in the area, and therefore have to be reached by means of two junctions connected together. These outgoing junctions on B-sections are known as 'lending' lines.

The incoming order wire or straightforward junctions are terminated in plugs and cords, and there is no apparatus on the key shelf beyond the plugs and lamp signals associated with them. Fig. 105 illustrates a typical B-position.

Monitor's Desk. In order to enable the A-operators to give a rapid and efficient service, special arrangements are made to enable them to transfer immediately to special operators any calls which require abnormal treatment, as, for example, calls for subscribers whose names do not appear in the directory, changed numbers, complaints, etc. The operators to whom such calls are transferred are called 'monitors,' and they are

accommodated at a special desk with a specially designed equipment.

A photograph of such a desk is given in Fig. 106. The following equipment is usually provided—

(1) Incoming lines from the switchboard. On the switch-

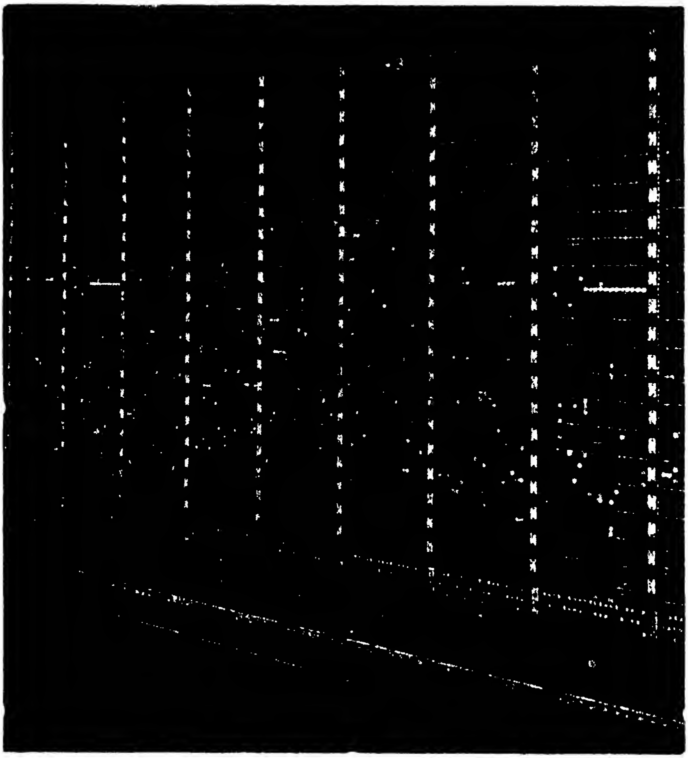


FIG. 105. B-POSITION

board these lines appear on the outgoing junction multiple, and are accessible to all operators; they terminate in jacks and lamps on the desk, and are used by the A-operators for passing on inquiries and complaints to the monitor.

(2) Outgoing lines to a B-position on the switchboard. These circuits enable the call to be extended to any subscriber on that exchange.

(3) Outgoing lines to an A-position on the switchboard.

These are used when it is desired to establish a connection with a subscriber on a distant exchange.

(4) Listening lines to all A- and B-operators' instrument circuits.

(5) Interception circuits. These can be connected to any

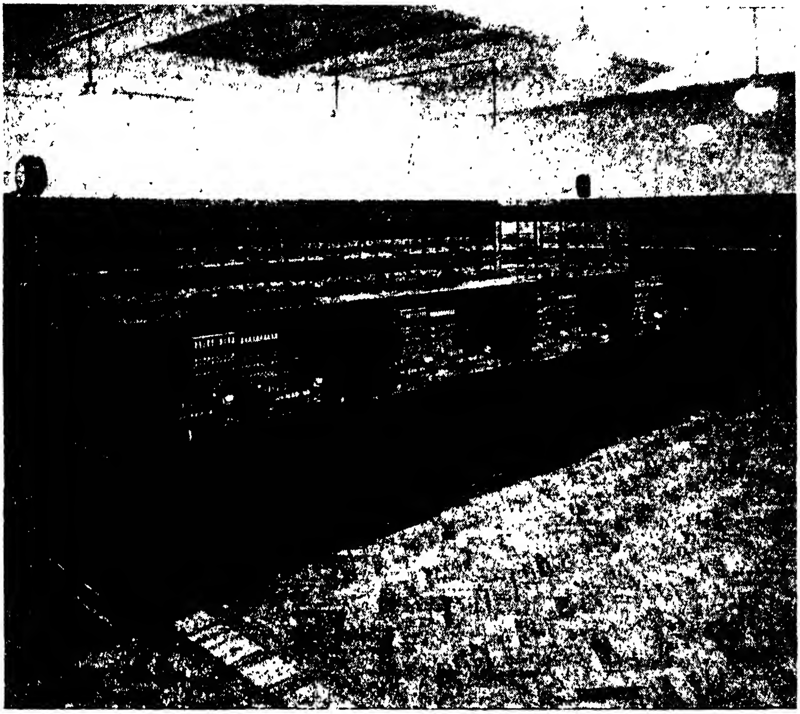


Fig. 106. Monitor's Desk
(*General Electric Co. Ltd.*)

subscriber's line in such a manner as to ensure that all calls from or for the subscriber set up on the main switchboard shall be completed and supervised by the monitor. They also afford a convenient means of dealing with directory errors or changed numbers, it being possible when the call is intercepted to inform the calling subscriber of the correct number before completing the call.

Each monitor's position is equipped with ten pairs of connecting cords, the circuit arrangements of which are very similar to the cord circuits on the ordinary A-operator's positions.

All faults are reported by the operators to the monitor, who enters details on a docket, which is passed on to the testing department for attention.

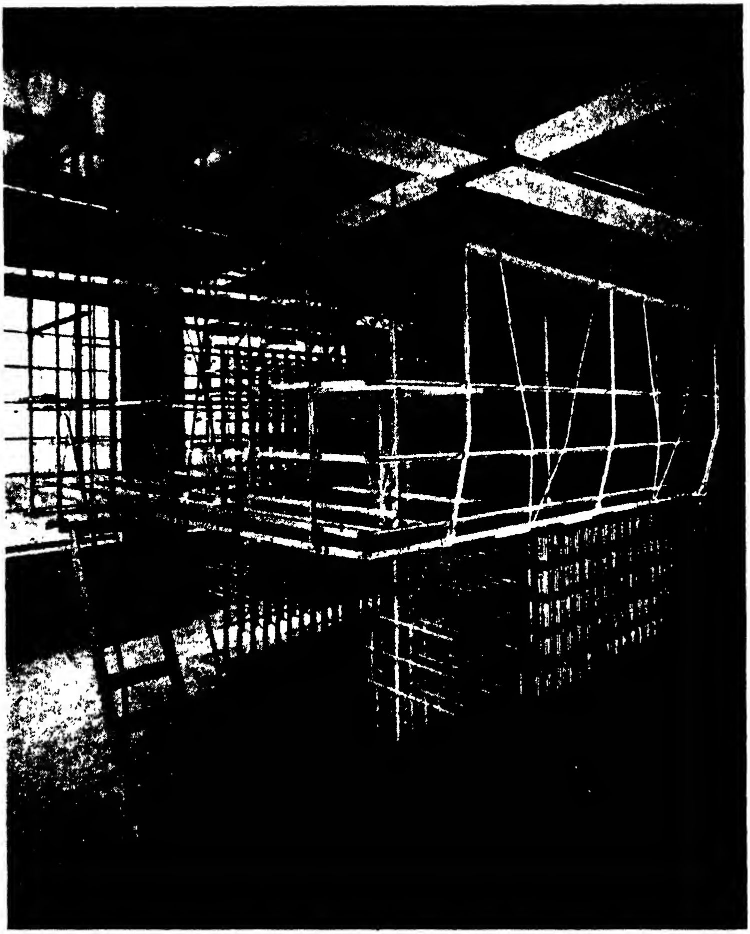


FIG. 107. MAIN DISTRIBUTION FRAME
(*Siemens Bros. & Co. Ltd.*)

Apparatus Room. In manual exchanges an apparatus room in close proximity to the switchroom is needed to accommodate the auxiliary apparatus in connection with the switchboard circuits, the various distributing frames, the testing equipment, and the power plant.

The street cables are brought through ducts or a subway into the basement, where they are supported on iron racks. If the apparatus room is above the ground floor the street cables are led up the walls supported on suitable racks, to a cable trench in the apparatus room floor beneath the main distribution frame. At this point the street cables are jointed on to lead covered silk and wool cables which pass through the floor and terminate on the verticals of the main frame.

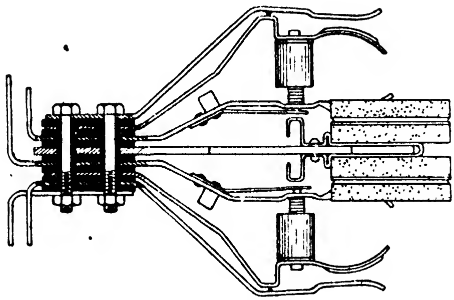


FIG. 108. LIGHTNING ARRESTERS

The construction of a main distributing frame is shown in Fig. 107. Its main members are the vertical angle irons. They are mounted at 8-in. centres along the whole length of the frame. Their bottom ends are bolted to heavy angle-iron floor plates and their tops are bolted to a continuous angle-iron which braces them all rigidly together. Horizontal cross-bars are fixed to each of these uprights in the manner shown, and the ends of these cross-bars are adapted to carry the line terminal and protective apparatus, and at the junctions of the central vertical angle irons and the horizontal cross-bars, the insulated jumper rings are fitted.

Lightning arresters and heat coils are combined in one fitting, accommodating the two wires of a circuit as illustrated in Fig. 108. They are designed to admit of a test plug being inserted without withdrawing the heat coils. The arresters are of the carbon type, having the mica separator and the plug of fusible metal. The heat coil (seen in section in Fig. 109) is placed between the springs as shown, the inner spring resting against a small brass collar soldered near the end of a thin brass rod by fusible metal. The resistance of the heat coil is

3·75 ohms. If, due to fault conditions, the current in the coil becomes too great (more than 0·35 ampere) the wire becomes heated, the fusible metal melts, and the outer spring then presses the whole coil inward until the end of the rod, passing through the collar, presses the light springs against the German silver strips, riveted on the thick iron bar, which forms the support for the whole strip. All the bars are connected to earth, and thus the line wire becomes directly earthed when the

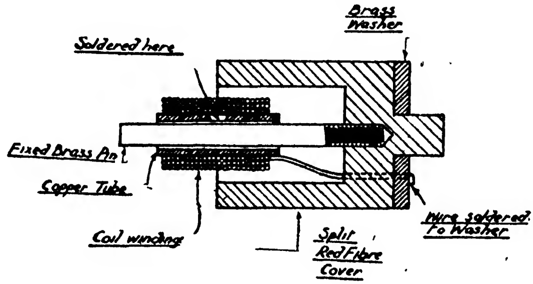


FIG. 109. HEAT COIL

heat coil operates. The current through the line is at once strengthened, and the line fuse (fitted between the heat coil and the line) melts, disconnecting the line from the exchange apparatus.

It should be noticed that when a heat coil is operated the exchange side of the line is earthed. In the case of the B-line this earth causes the subscriber's calling signal to glow and thus draws attention to the fault. A similar trouble on the A-line interferes with the operation of the supervisory lamps on the cord circuits, and so attracts the operator's attention when the next attempt is made to set up a connection.

The fuses are mounted on the line side of the frame and are mounted on strips carrying twenty pairs. The fuse and fuse mounting is illustrated in Fig. 110. The centre steel plates marked *A* are bolted vertically on to the horizontal cross-bars on the main frame, so that when completely equipped the fuses are arranged in parallel vertical rows with gaps between each set of 20 pairs. A wooden fanning strip is fitted on each mounting, and the wires from the street cables pass to the fuses

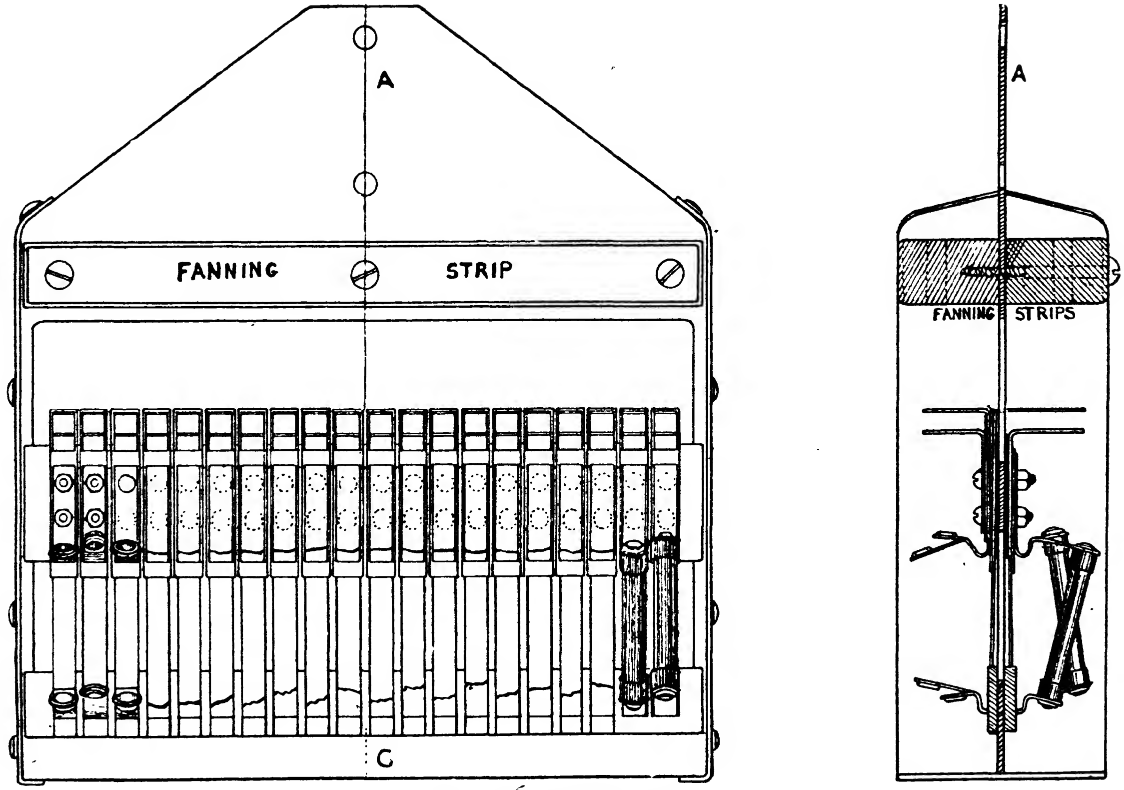


Fig. 110. Fuse Mounting

through the holes on one side and the jumper wires on the other. The fuses for the A- and B-wires of a loop are located on opposite sides of the centre plate, the tab connections being carried over by the fixing bolts in the case of one wire, and by the springs passing through a hole in the plate for the other wire. To facilitate their removal alternate fuses are staggered.

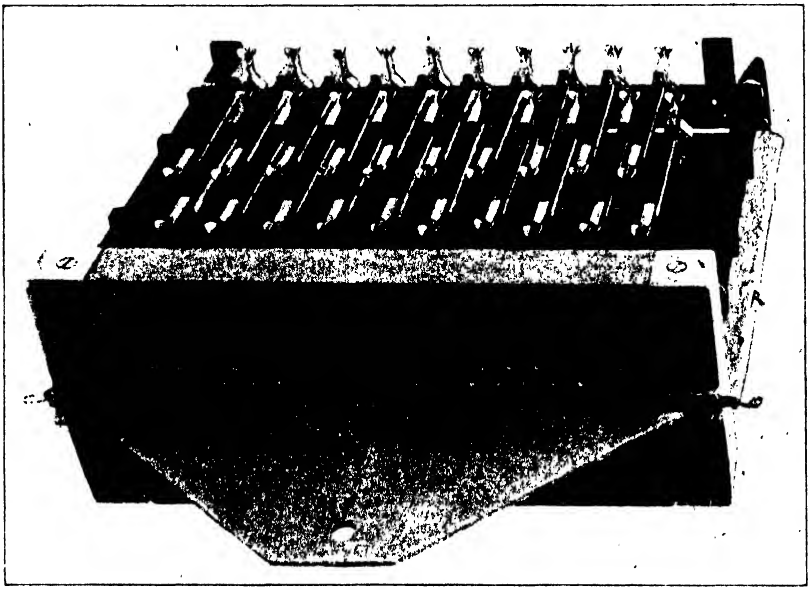


FIG. 111. JUNCTION TYPE FUSE MOUNTING

A different type of fuse mounting is used to terminate trunk and junction cables, and is specially designed to give high insulation resistance. In order to obtain space for insulating material between the tags it is made to open across its centre, and is provided with a dustproof cover (Fig. 111).

Main Distribution Frame (M.D.F.). The street cables are terminated on adjacent mountings in the same vertical if possible, but in any case so as to expose a minimum amount of the insulated conductor.

On the exchange side of the frame the circuits are wired in numerical order, and are connected to the switchboard multiple via the multiple side of the Intermediate Distribution Frame (I.D.F.). On the M.D.F., the circuit with the multiple number

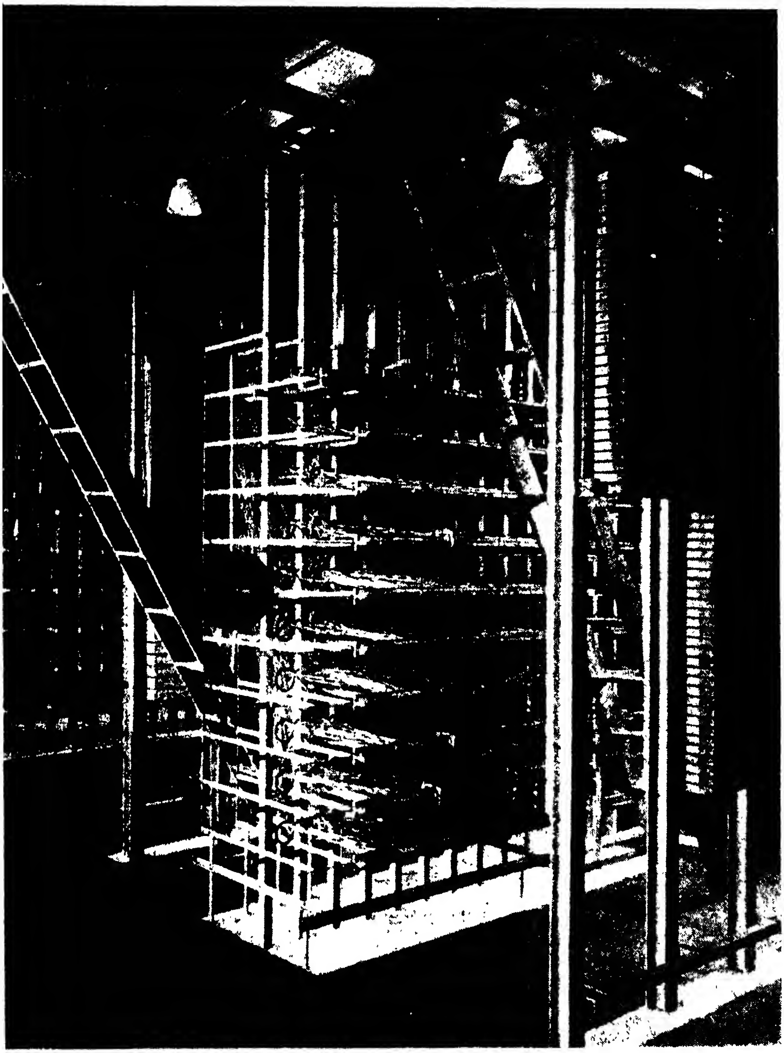


FIG. 112. INTERMEDIATE DISTRIBUTION FRAME
(*Siemens Bros. & Co. Ltd.*)

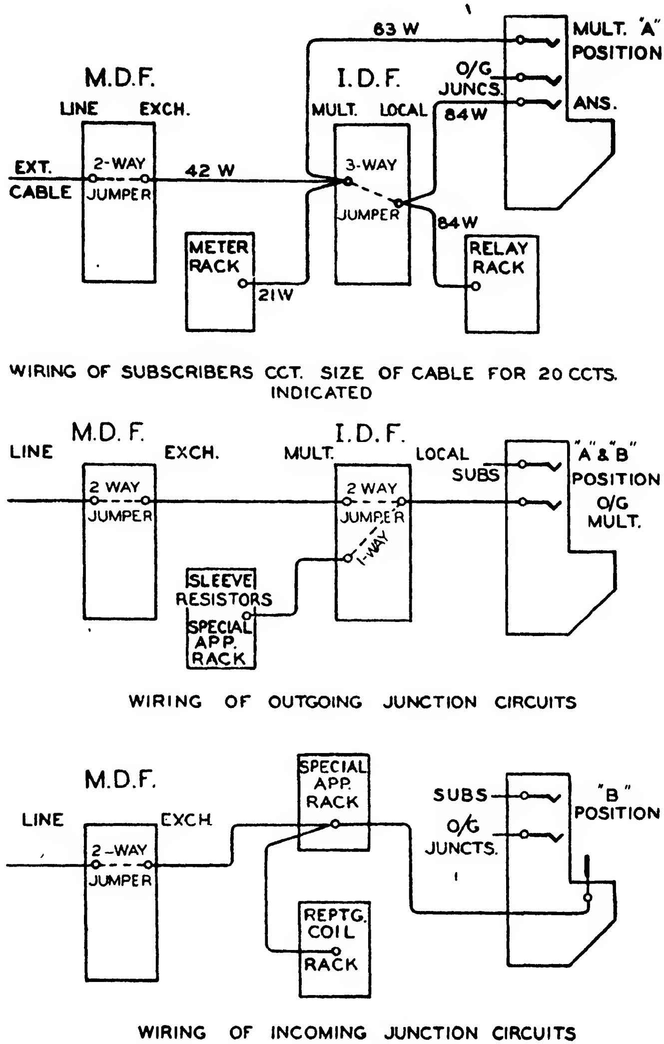


FIG. 113. C.B. EXCHANGE CABLING ARRANGEMENTS

allotted to a given subscriber is cross-connected to the external cable pair for that subscriber by means of a flexible two-way jumper, and reallocation of ceased lines, or the picking up of spare circuits, can easily be carried out at this point without interference with the exchange equipment.

Intermediate Distribution Frame (Fig. 112). The Intermediate Distribution Frame serves to even up the load on the switchboard positions. On the multiple side, verticals carry tag-blocks, to each of which are cabled twenty circuits from the M.D.F., in proper numerical sequence. From the same tags,

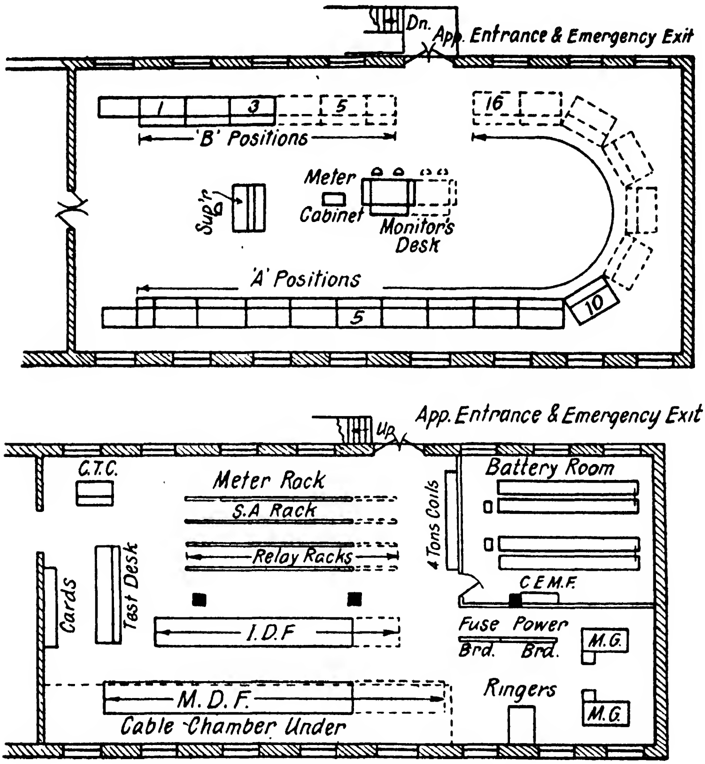


FIG. 114. APPARATUS ROOM LAY-OUT

the multiple cables are taken to the switchboard jacks, two complete sets of cables being used if the A- and B-positions are in separate suites. The multiple cables consist of three conductors (tip, ring, and sleeve), whilst the cables to the M.D.F. carry only the A- and B-wires (joined to tip and ring respectively). On the same tag blocks, separate cables carrying twenty single-wire circuits to the meter rack are connected, as these meters are arranged in numerical order to facilitate the periodical reading of the calls registered.

The local side of the I.D.F. is arranged to take either horizontal or vertical rows of tag blocks. In either case, four-way tag blocks are used, and two sets of cables are taken respectively to the relay racks and home section jacks of the A-positions. The four wires concerned are the tip, ring, sleeve, and lamp conductors. Battery for the lamp is supplied from the switchboard via the line lamp pilot relay. The line and cut off relays are mounted on racks generally arranged to line up parallel with the I.D.F. for convenience in cabling. The tip ring, and sleeve conductors on the I.D.F. multiple side for any given line are cross-connected by a three-way jumper to a calling equipment on any chosen position. The position loads are equalized by re-jumpering if necessary, without disturbing any permanent cabling. The answering jacks and lamps on the switchboard are labelled to indicate the multiple number connected. In some exchanges, duplicate appearances of the answering lamps and jacks are provided. Calls may be answered by operators having access to either jack, and this system is termed *ancillary* working. It is particularly suited to exchanges with busy hour traffic much in excess of normal, as during a large part of the day operators may be concentrated on one half only of the switchboard.

Incoming, outgoing, and bothway junctions are also cabled via the I.D.F. and M.D.F., the necessary relay equipments being cross-connected at the former. Typical cross-connection schemes, cabling, and layout arrangements for a C.B. exchange are shown in Figs. 113 and 114.

CHAPTER VII

RELAYS

THE electromagnetic type of relay used in telephony is made in various forms by different manufacturers, but the same electrical principles apply to all types.

The following detailed descriptions refer to the P.O. 3000 type relay, which is now standardized for automatic exchanges. It is somewhat similar to the earlier Siemens relay, used for many years on manual and automatic apparatus. Figs. 116, 117, 118, and 119 illustrate the construction.

Relays may be mounted singly, wired in strips, or assembled in relay sets (Fig. 115), as required. The mounting position is arranged where possible so that the flat surface of the contact springs is in a vertical plane, preventing the accumulation of dust on the contacts.

Relays are assembled from standard components, details of which are as follows.

Magnetic Circuit. The *core*, the *yoke*, and the *armature* comprise the magnetic circuit. These parts are made of soft iron, and are nickel plated to avoid oxidization. The joint between the core and the yoke is carefully made to ensure a good magnetic path.

Core. This is a plain cylinder of soft iron, enlarged at the pole face so as to reduce the reluctance of the magnetic circuit. Where high impedance coils are desired, nickel iron sleeves (Fig. 120) are fitted over the core before winding, thereby increasing the impedance of the latter.

On ordinary relays, a copper front cheek is fitted to the core, its effect being to steady any erratic movement of the armature by virtue of the eddy currents which will be induced in the cheek. The copper cheek is replaced by one of bakelite when the relay is required to be particularly fast to operate, or when nickel iron sleeves are used.

Slugs. Solid copper slugs, of cylindrical form, are employed at the armature or heel end of the core to give a delayed operation or release, or both. Three lengths of slug, ½ in., 1 in., 1½ in., give various degrees of delayed action.

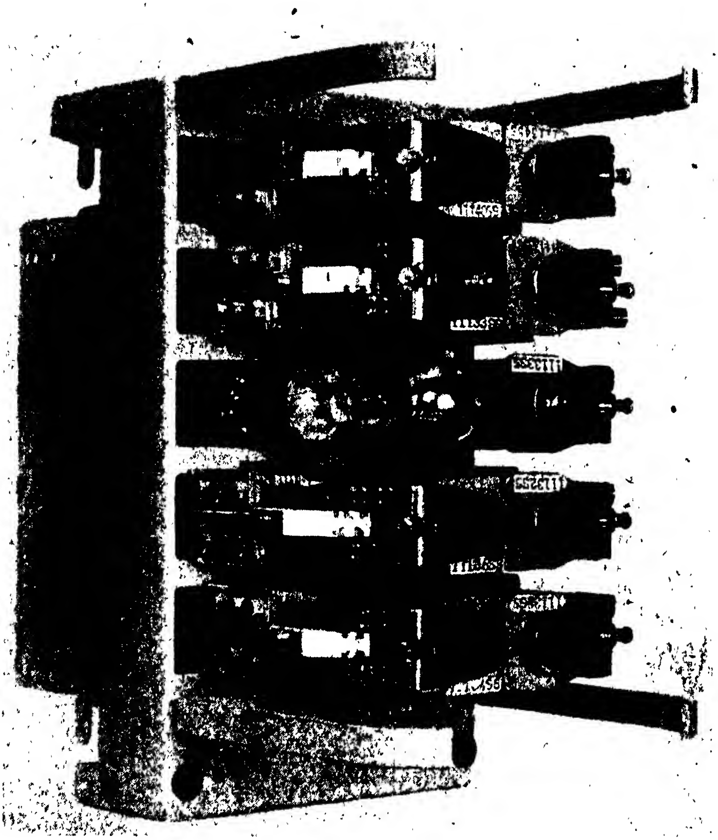


FIG. 115. RELAY SET
(*Siemens Bros. & Co. Ltd.*)

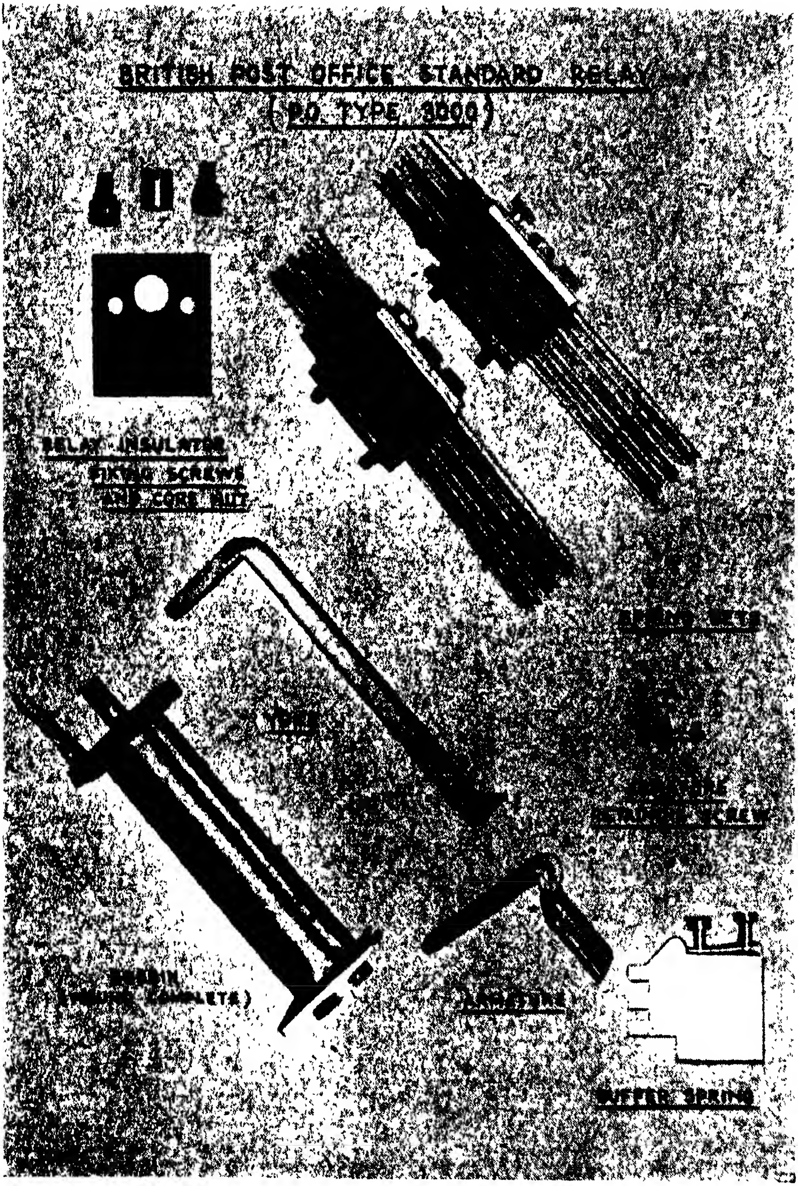


FIG. 116. COMPONENT PARTS OF RELAY
(*Siemens Bros. & Co. Ltd.*)

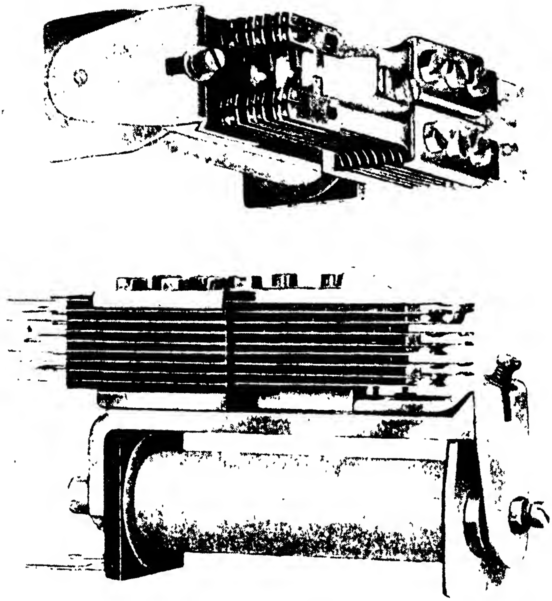


FIG. 117. P.O. 3 000 TYPE RELAY
(*Siemens Bros. & Co. Ltd.*)

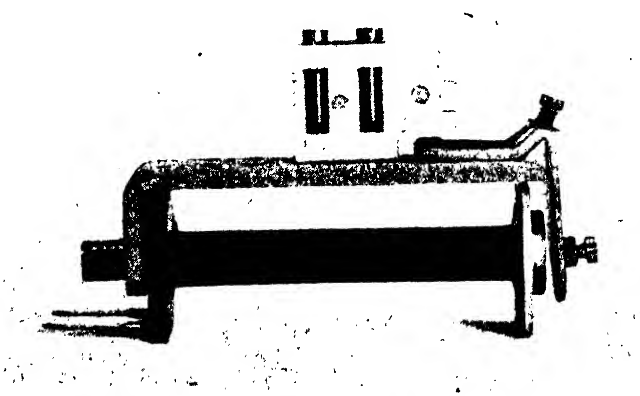


FIG. 118. SKELETON OF RELAY
(*Siemens Bros. & Co. Ltd.*)

Armature (Fig. 119). The armature may have a fixed residual stud of thickness 4, 12, or 20 mils, depending on circuit requirements. A phosphor bronze pin of the length required is used, and where a particular timing requirement has to be met, an adjustable screwed pin may be employed instead.

An 'isthmus' armature is used on impulsing relays, the reduced cross-section resulting in saturation of the magnetic circuit at a low value of ampere turns, thereby giving more

FIG. 119. TYPES OF ARMATURE
(*Siemens Bros. & Co. Ltd.*)

constant performance under varying line conditions and a lower release period. As the armature (Fig. 119) is lighter, it also responds more readily to dial impulses.

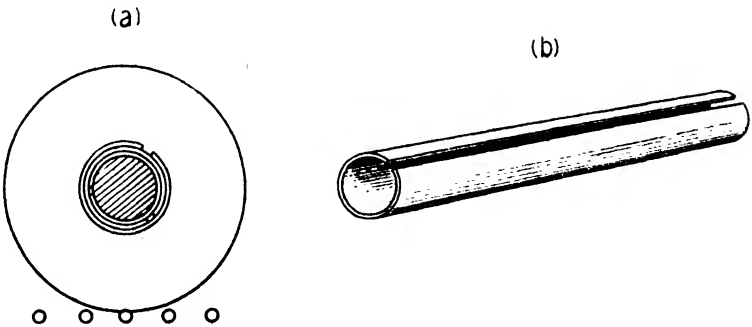


FIG. 120. NICKEL IRON SLEEVES

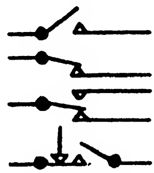
Yoke. This consists of an L-shaped piece of soft iron, with a knife edge at the extremity, on which the armature is pivoted. The core is inserted into the turned-over end, and the contact assemblies and buffer block are screwed to the flat portion.

Coil. The coil is wound on an insulated spool, fitted over the core, the terminations of the winding being brought out to tags at one end (the rear)—one, two, or three windings on one spool may be obtained. The design of the coil is dealt with later.

Buffer Block. This is of white synthetic material, and provides suitable steps against which the 'buffered' springs are tensioned, thereby restraining them in the correct position, above or below the lever springs actuated by the armature.

Spring-sets. The contact springs, of nickel silver, are 14 or 12 mils thick, depending on the tension required. The contact pips are duplicated on each spring, and are usually of pure silver. Platinum is used for heavy duty contacts (i.e. those in magnet circuits). The spring-set units are of four types—

Single make.
Single break.
Change-over (break-make).
Change-over (make-then-break).



SPECIAL RELAYS

Ordinary relays may be made fast to operate by the omission of the copper front cheek, or fast to release by employing a large residual air gap.

Slow operation or release is obtained by the aid of slugs or short-circuited windings. Some other special requirements are met by the following expedients.

A.C. Relays. For operation on alternating current, an ordinary relay shunted by a small half-wave rectifier is used. The current passes through the rectifier during one half-cycle and through the relay coil during the next.

The current in the coil is thus always in the same direction, and moreover the rectifier acts as an efficient short circuit during the conducting half-cycle, since any induced current in the coil may continue to flow through the rectifier.

Shunt Field Relays. A shunt field relay (Fig. 121) is used to detect the reversal of polarity of a current in one of its windings. The magnetic circuit is shown in Fig. 122. Normally, the relay is polarized by a current in the local winding as soon as the

circuit in which the relay is employed is taken into use. Alternatively, a small permanent magnet can be used instead of the polarizing coil.

The flux thus produced passes through the second core, which completes a closed magnetic circuit, without attracting the armature. For non-operation of the relay, any current in the

FIG. 121. SHUNT FIELD RELAY
(*Siemens Bros. & Co. Ltd.*)

line coil (on the second core) must flow in such a direction that the flux due to the polarizing coil is assisted, and the armature therefore remains unaffected. If now the current in the line winding is reversed, the two fluxes oppose, and both combine in the alternative path via the armature and yoke, thus operating the relay.

Thermal Relays. Where a very long operate or release lag is required, a thermal relay is employed.

A standard yoke is used, and mounts the thermal element, a spring-set, and a special spring where desired, to produce a 'flick' action. The thermal element consists of a bi-metallic strip, overwound with resistance wire, through which the operating current is passed. The heat thereby produced causes unequal expansion of the strip elements, and the element 'bows,' until the tension exerted on the 'flick' spring causes

the latter to change over and bow in the opposite direction, making contact with a separate spring on the assembly, and closing an external circuit. (See Fig. 123.) A similar bi-metallic

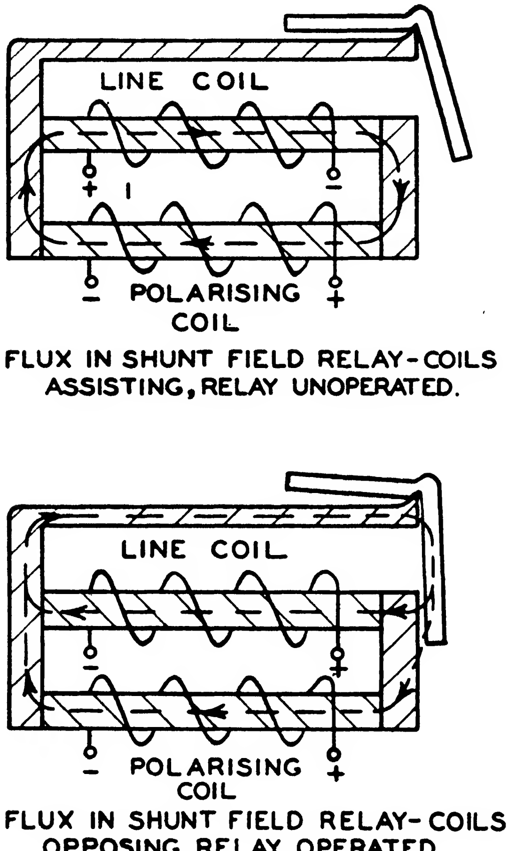


FIG. 122. MAGNETIC CIRCUIT S.F. RELAY

strip, unwound, supports the spring assembly from the opposite side, and automatically compensates for any temperature changes in the surrounding air.

If the 'flick' action is not used, the strip may actuate a spring-set directly, provided ample 'follow' is allowed on the springs, and a transit clearance given to prevent all springs making together. Operating lags of from 10 to 60 sec. may be

obtained, and the release time is about 15 sec. A relief relay must be employed if more than one spring-set is required.

Relay Switches. These are employed for all heavy current work, and consist of relays actuating mercury tubes, which rock on an axis to give alternative connections.

The exchange type occupies the space of two relays on an ordinary mounting plate, and can carry two tubes, each capable of making or breaking currents up to 6 amperes. This type is non-locking, and restores to normal when the current ceases to flow in the relay coil.

The heavy duty type, used in mains supply and power plant switching, is contained in a metal housing, and an example is shown in Fig. 124. Various forms of mercury tubes may be employed, some giving quick action, and some delayed action. The operation of the various tubes will be clear from the illustrations in Fig. 125. The delay-type tubes are used in the 'Parallel Battery Float' power plant, described in Chapter IX.

Mercury tubes may be employed in any switchgear, and may include special operate and reset actions, utilizing two cores and separate windings. They may also be actuated mechanically, in preference to using multi-bladed switches.

Delayed Action Relays. Some relays, particularly those in alarm circuits, are required to operate after connection of the current for a specified number of minutes. One type consists of a solenoid, the core of which is restrained by an oil dashpot, and moves slowly into the hollow coil until the contacts operate.

Alternatively, a fast relay may be employed, which controls a pulsing circuit to a uniselector, the latter being stepped forward every 30 sec. so long as the relay remains operated. The alarm circuit is completed by the wipers at a predetermined point by wiring out the appropriate bank contacts.

Relay Design. The behaviour of a relay is determined by its spring load, ampere turns on core, and air-gap at armature. The spring load is determined by the circuit requirements, and must not exceed certain limits.

For each spring-set load there is an equivalent number of ampere-turns which will operate the relay, and to ensure a satisfactory performance, and to avoid the necessity for frequent readjustment, a substantial factor of safety is allowed in the design.

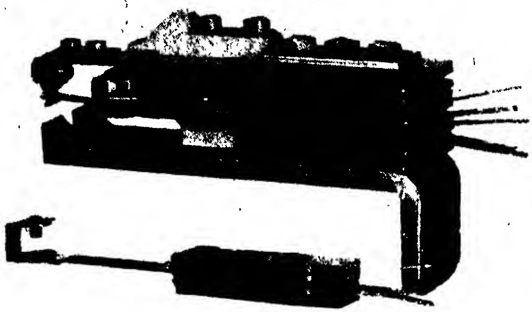


FIG. 123. THERMAL RELAY
(*Siemens Bros. & Co. Ltd.*)

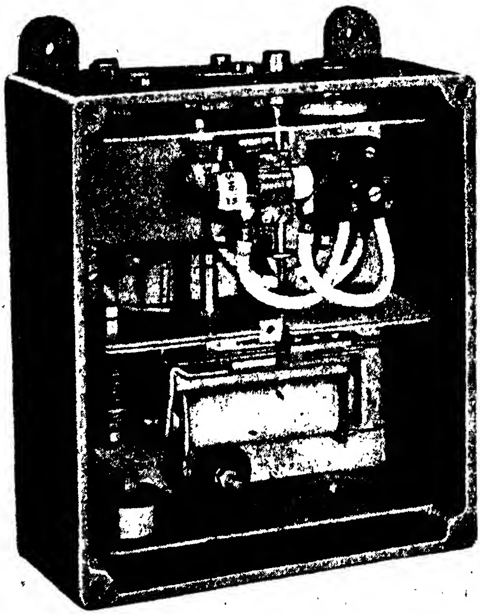


FIG. 124. MERCURY CONTACT RELAY
(*Siemens Bros. & Co. Ltd.*)

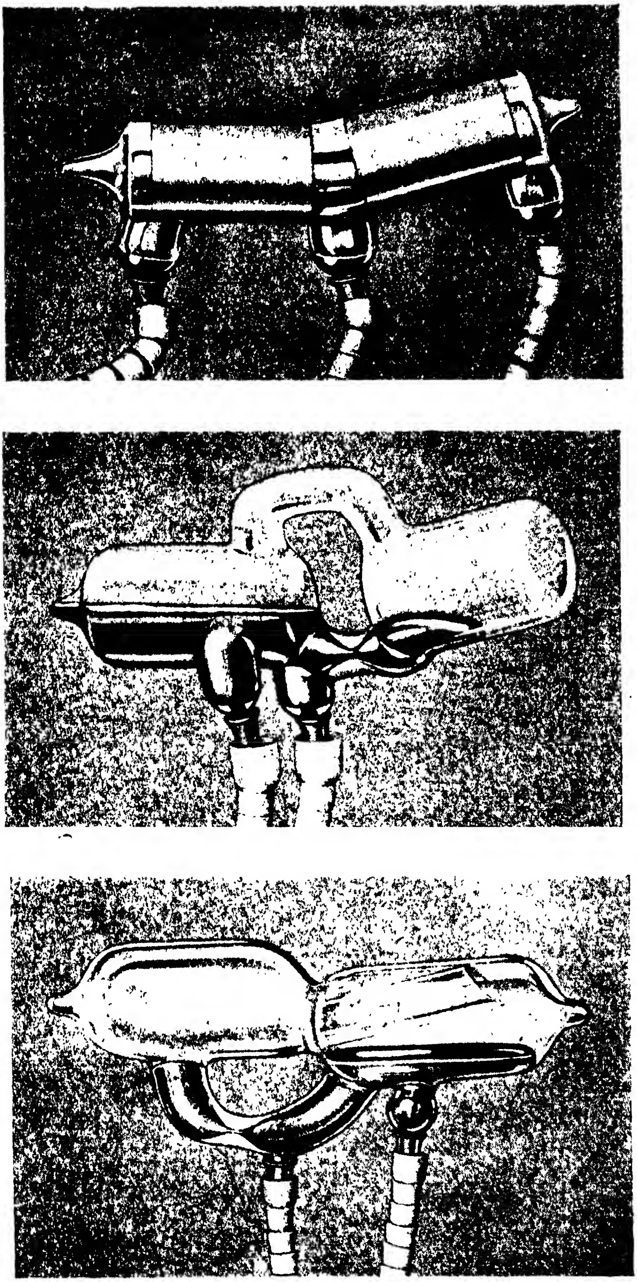


Fig. 125. Mercury Tubes
(*Siemens Bros. & Co. Ltd.*)

Factors of Safety. The following values are obtained whenever possible.

(a) Operate $\dfrac{\text{Circuit Ampere-turns}}{\text{Operate Ampere-turns}} = 4$

(b) Non-operate $\dfrac{\text{Circuit Ampere-turns}}{\text{Non-operate Ampere-turns}} = \dfrac{2}{5}$

(c) Hold $\dfrac{\text{Circuit Ampere-turns}}{\text{Hold Ampere-turns}} = \dfrac{5}{2}$

(d) Release $\dfrac{\text{Circuit Ampere-turns}}{\text{Release Ampere-turns}} = \dfrac{1}{3}$

The circuit ampere-turns in each case are those obtaining under the particular conditions, i.e. hold, release, etc., after due allowance has been made for extreme battery voltage, and permissible resistance variation of the coil.

As standard parts are used for assembling the relays, once the pull exerted by the armature for given numbers of ampere-turns on the core has been found, then the pull for any value of ampere-turns can be deduced from a graph (Fig. 126).

The pull is equal to—

$$B^2a/8\pi \text{ dynes}$$

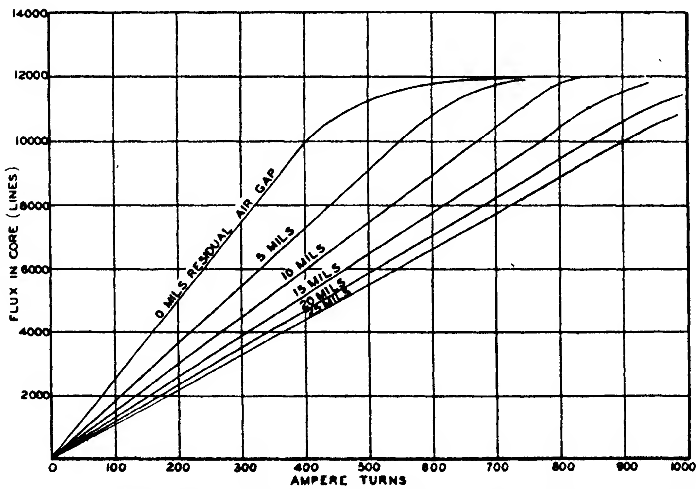


FIG. 126. VARIATION OF TOTAL FLUX WITH AMPERE TURNS ON CORE

where B is the flux density, and a is the area of pole face in square centimetres. As the latter does not change, the pull is proportional to the square of the flux, and hence to the square of the ampere-turns as long as the iron circuit is not saturated (Fig. 127).

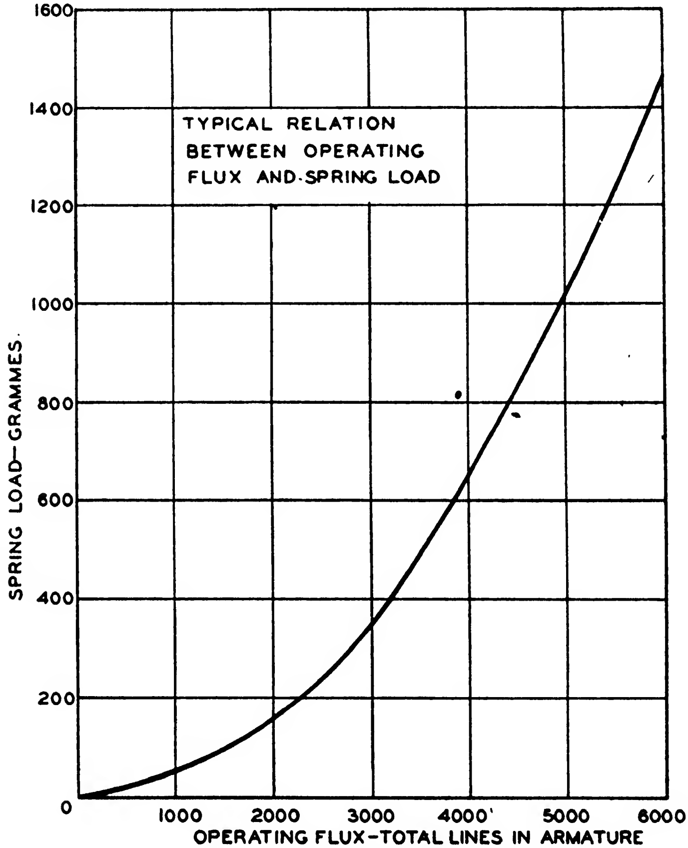


Fig. 127. Operating Flux in Relation to Spring Load

To design the coil, the number of ampere-turns to operate the spring-set is found, and multiplied by the relevant factor of safety.

This number of ampere-turns in the coil should be a little lower than the saturation value, otherwise the safety margin is only apparent. The residual air-gap can only be determined by experiment, and will depend on the release time required.

Approximate values for given numbers of ampere-times can be found from a curve. If the timing is critical, then an adjustable residual pin should be fitted, and correction made within certain fixed limits.

The coil should be fully wound, so as to economize in current.

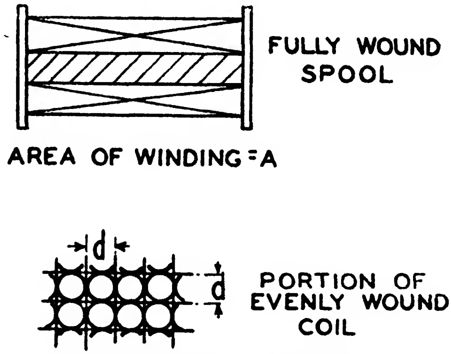


FIG. 128. WINDING OF RELAY COIL

If the cross-sectional area of one turn is a, and of the whole winding is A (Fig. 128),

Then resistance of winding of T turns $= R = \rho Tl/a$ where ρ is the resistivity of copper, and l is the mean length of a turn, i.e. $\dfrac{\text{length of shortest} + \text{length of longest turn}}{2}$

This will be constant for a fully wound coil.

If the diameter of the wire is d, its cross-sectional area is $\pi d^2/4$, and if the turns lie evenly, the space occupied by T turns will be Td^2.

This is equal to A, or $d^2 = A/T$.

$$\therefore \qquad R = (\rho Tl/d^2)(4/\pi) = (4\rho l/\pi A)\,T^2,$$

$$\text{or} \qquad R = K \,.\, T^2 \text{ for a fully wound coil.}$$

The fact that the resistance is proportional to the square of the turns shows that if more ampere-turns are required, it will be necessary to reduce the resistance. For example, if one fully wound coil has 10 000 turns and a resistance of 1 000 ohms,

at 50 volts, ampere-turns $= (50/1\,000) \times 10\,000 = 500$;

but since $R \doteq K \,.\, T^2$, $K = R/T^2 = \dfrac{10^3}{10^8} = 10^{-5}$

and if, say, 700 ampere-turns are needed,

then $$700 = (50/R)T = 50T/KT^2$$
$$= 50/KT,$$
or $$T = 50/700K$$
$$= 50/(7 \times 10^{-3})$$
$$= 7\ 143 \text{ ampere-turns approx.}$$

and the resistance will be $K \cdot T^2$, or 500 ohms.

Similarly, the turns and resistance of any other winding may be deduced once the value of K has been established.

Timing. Suppose a relay has a resistance of 1 000 ohms and an inductance of 5 henries.

With a factor of safety of 2·5, the relay should operate with 20 mA. in a 50-volt circuit.

Now the value of the current t sec. after switching on is given by Helmotz equation,

$$i = (E/R)\,(1 - e^{-Rt/L}).$$

To find the time taken for the current to rise to its operating value,

$$iR/e = 1 - e^{-Rt/L}$$
$$1 - iR/e = e^{-Rt/L}$$
$$-Rt/L = \log_e (1 - iR/E)$$
$$= \log_{10} 0{\cdot}6/0{\cdot}4343$$
$$= -0{\cdot}51,$$
or $$t = 0{\cdot}51 \times 5/1\ 000 = 2{\cdot}5 \text{ msec.}$$

This time will be increased if the inductance is raised or the resistance lowered, and to it must be added the time taken for the armature to move into the operated position. This latter period will depend on the *stroke* or armature travel of the relay, and on the spring load. It will vary from 5 msec. with a short stroke and moderate spring load, to 50 msec. with a long stroke and heavy loading.

Release Time. The current flow ceases immediately the circuit is broken, as the conditions are not such as to render arcing at the contacts probable. The flux dies away fairly rapidly if the residual air-gap is large, but may take an appreciable time if the gap is small, since in the latter case the effects of residual magnetism are most marked. As soon as the pull

on the armature fails to counteract the spring load, the armature restores. Releasing times on normal relays vary from 5 msec. to 30 msec.

Slugs. The operating and releasing lags can be artificially increased by means of *slugs* or rings of copper mounted on the core. They vary in length from ½ in. to 1½ in. and are of the maximum diameter that can be accommodated. A slugged

Fig. 129. Slugged Relay
(Siemens Bros. & Co. Ltd.)

relay is shown in Fig. 129, and the magnetic effect is indicated in Fig. 130.

When the current in the main coil is switched on or off, a current will be induced in the copper slug.

By Lenz's law, the current will be in the opposite direction to the main current on switching on, and in the same direction on switching off. There will be no effect during the steady state condition.

The reason for a solid slug can now be seen: with a given induced voltage, maximum ampere-turns can be obtained with a winding of minimum resistance, and the flux due to the slug is therefore considerable. Its effect will depend on—

(*a*) the direction of induced current (opposing or aiding);

(*b*) the position of the slug on the core.

Consider the operating condition. The fluxes oppose at the slugged end of the core, but no effect is experienced at the

unslugged end. If, therefore, the slug is at the armature end of the core, the relay will be slower to operate, and lags of up to 150 msec. can be obtained by a slug in conjunction with a large stroke and heavy tension in the springs. If mounted at the heel end, no effect will be felt on operation.

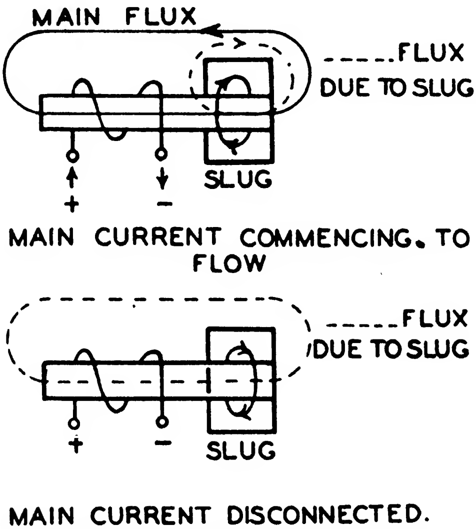


FIG. 130. RELAY COILS AND SLUGS

On release, the induced current in the slug maintains the flux in the same direction, and thus keeps the armature attracted until the induced current dies away. As there is no opposition flux, the effect is the same whether the slug is mounted at the heel or armature end, and with a small residual air gap and light spring tension it is possible to get lags up to 500 msec. with slugged coils.

It is usual to place the slug at the heel end if slow release only is required.

Less space is of course available for the coil when a slug is used, and the term *A* in the formula for resistance must be reduced accordingly.

The effect of slugs can be reproduced to nearly the same extent by a short-circuited winding, or by shunting the main winding with a low resistance or short circuit on release. The advantage of this device is that the control of the timing can

be devolved on the relay's own contacts, and slow operation plus quick release, or vice versa, can be obtained.

A few circuits are shown in Fig. 131 which give the various conditions.

Relays used in line circuits must operate and release satisfactorily with the minimum and maximum currents likely to

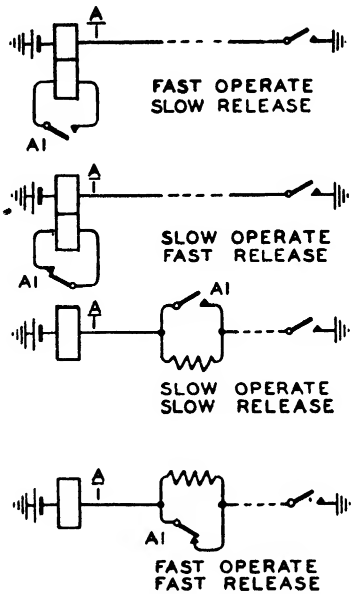


FIG. 131. TIMING CONTROL OF RELAYS

be met. If the relay is used for impulsing, it is usual to fit the 'isthmus' type of armature, which is designed so that the iron circuit is saturated with fewer ampere-turns than those normally required. This feature, in conjunction with a large residual air-gap, ensures that the releasing lag shall be reasonably constant with varying line conditions. A certain amount of sensitivity is, of course, sacrificed for this facility, and it is customary for impulsing relays to have but one contact assembly.

Adequate contact pressure is essential if a reliable performance from a relay is desired. Springs tensioned against the buffer block should require a pressure of at least 11 gms. to lift them from the block. Lever, or moving, springs should be

tensioned to exert a pressure of 5–8 gms. on the lifting pin, which bears on to the armature.

These figures are minimum values, and may be considerably increased by the use of stouter springs, or by bias springs if necessary, in order to impose a greater load on the armature for quick release purposes.

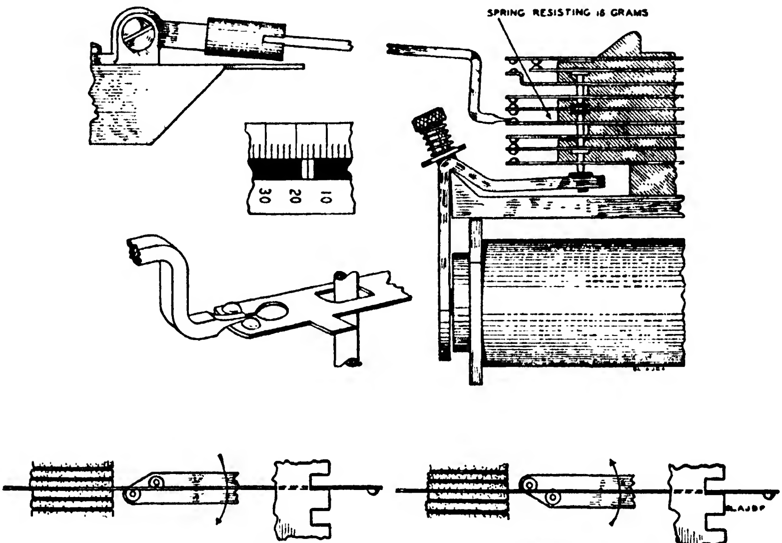


FIG. 132. MEASURING SPRING TENSIONS

The contact pressures are measured by means of a tension gauge (Fig. 132), and varied with a tool shaped so as to add or remove tension from the spring when used in the appropriate way.

Sometimes it is desired that a certain contact or contacts on a relay should operate earlier or later than the remaining contacts. This feature should be avoided if possible by re-designing the circuit, but may be obtained, where essential, by special adjustment of the springs. Contacts which operate earliest are sometimes designated by the suffix x, and those operating late by y.

Impulse Distortion. A point of great importance in the behaviour of impulsing relays is the problem of distortion. If a relay has equal operating and releasing lags, its contacts will

reproduce exactly the makes and breaks of the line current, and impulses from a dial can be relayed by such a relay without distortion. This will only be possible however for one value

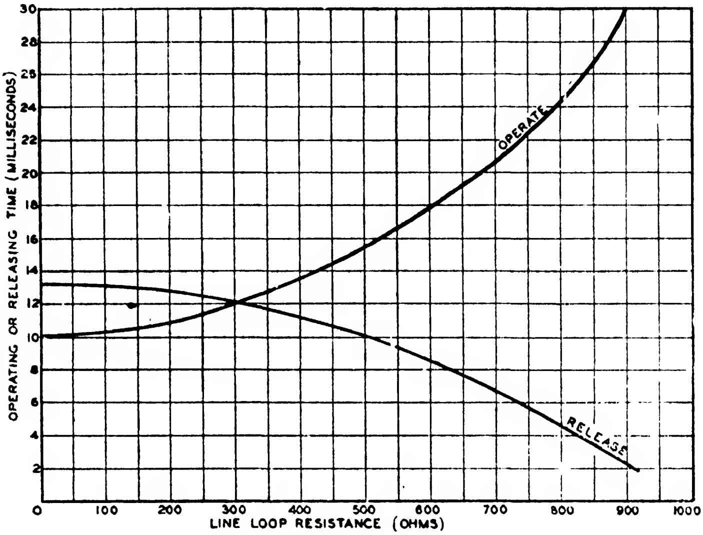


FIG. 133. TIMING OF IMPULSING RELAY

of line resistance and battery voltage, and for any other conditions distortion will result, as shown in Fig. 133.

If the line resistance is increased, or the battery voltage lowered, the relay will be slower to operate and quicker to release, due to the decrease in the ampere-turns.

The reverse applies in the case of a lower resistance line and higher battery voltage, while the presence of condensers or low insulation between line and earth, will further affect the behaviour of the relay.

Rectifier Shunts. If a relay coil is shunted by a rectifier, with the latter connected so as to oppose the passage of current when the operating voltage is applied, the relay will release slowly on the circuit being broken, as the induced E.M.F. in the coil will cause a current to circulate in the coil and rectifier in series, thus retaining the armature attracted until the current falls below the hold value. Longer lags can be obtained than by using non-inductive shunts, as the rectifier forms a virtual short circuit on the coil under release conditions.

CHAPTER VIII

BATTERIES

MOST telephone apparatus requires a supply of direct current for its proper functioning, and the various means of obtaining this will now be considered.

PRIMARY CELLS

These are suitable as a source of energy when the average discharge current is low (500 mA. or less), and where the mean voltage need not be maintained closer than $\pm$ 25 per cent. The only type of primary cell used in Telephony is the Leclanché, which is made in both the *wet* and so-called *dry* form.

The *wet* cell consists of a glass or earthenware container, a zinc rod, a porous pot (or linen sac) (Fig. 134), in which a central carbon rod is tightly packed round with manganese dioxide; and a solution of ammonium chloride (sal ammoniac). The latter is termed the *electrolyte*, and the zinc and carbon electrodes are immersed in it. Suitable terminals permit connection to an external circuit.

The *dry cell* has the same chemical constituents, but the zinc electrode is formed into a container for the active material, which is mixed with various inert agents, to form a paste. The carbon positive electrode, surrounded by the canvas sac containing the depolarizer, is inserted in the centre, and the top is packed with sawdust, or other absorbent material and then sealed with pitch, small vents being provided for the escape of gas. The brass terminal of the positive pole protrudes from the top, and a flexible insulated wire is soldered to the zinc container to serve as the negative connection. Fig. 136 gives a sectional view of one of these dry cells.

The theory of operation is as follows—

When the external circuit is completed, the zinc negative electrode is attacked by the ammonium chloride, and zinc chloride, ammonia gas and hydrogen are formed. The zinc chloride and ammonia dissolve in the electrolyte, whilst the hydrogen appears as small bubbles of gas on the positive carbon electrode. Here it combines with the manganese dioxide to form water and a lower oxide of manganese (sesquioxide).

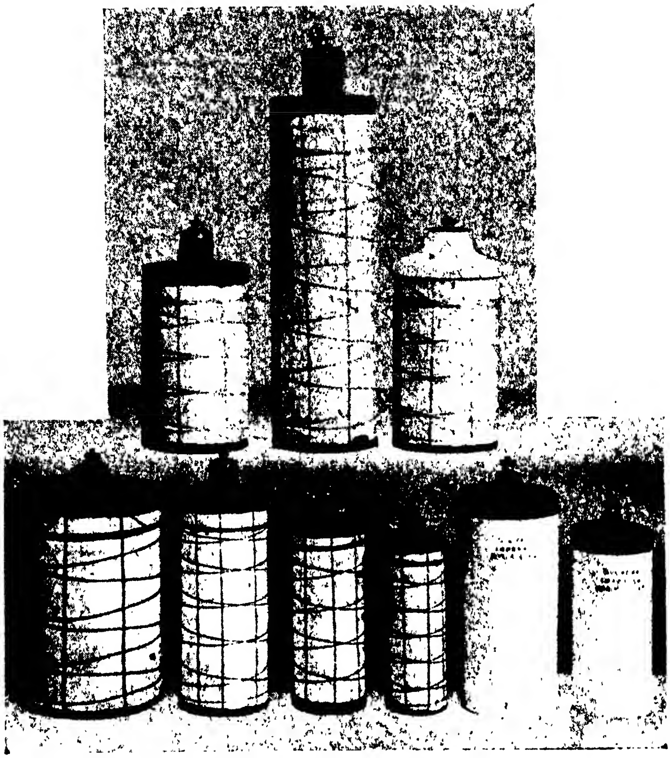


Fig. 134. Leclanché Cell
Depolarizing elements.
(*Siemens Bros. & Co. Ltd.*)

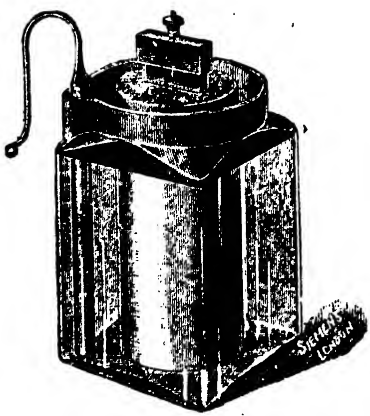


Fig. 135. Leclanché Cell
Wet type.

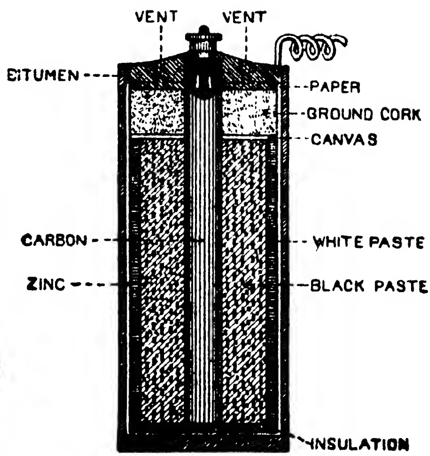


Fig. 136. Section of Dry Cell

Expressed symbolically, the action is—

$$Zn + 2NH_4Cl = ZnCl_2 + 2NH_3 + H_2$$

in the outer cell, and

$$H_2 + 2MnO_2 = H_2O + Mn_2O_3$$

in the porous pot. Points to be noted are—

(*a*) The carbon electrode plays no part in the chemical action.

(*b*) The zinc is gradually dissolved, and the ammonium chloride changes to zinc chloride.

(*c*) The ammonia gas dissolves in water to form ammonium hydrate, but gives off fumes of ammonia.

(*d*) No action takes place until the external circuit is closed.

Polarization. If a heavy current is taken from a Leclanché cell for a few minutes, the manganese dioxide surrounding the carbon electrode is unable to dispose of the whole of the hydrogen liberated. The positive pole therefore tends to become insulated by a film of hydrogen, and the cell is said to be *polarized*. Besides interfering with the chemical action, the film of hydrogen effects a large increase in the internal resistance of the cell, and the current drops rapidly to a very low value. If the cell is disconnected from the circuit, it soon recovers its normal properties, and is therefore most suitable for use in circuits where current is only required intermittently, as in subscribers' local battery telephone instruments and bell circuits.

E.M.F. The electromotive force of the Leclanché cell is independent of its dimensions, and is 1·4 to 1·45 volts when the cell is new. It drops a little as the chemicals become exhausted, and the cell should be recharged with fresh solution periodically, the zinc and depolarizing elements being replaced as the necessity arises.

Internal Resistance. The internal resistance of a 'dry' Leclanché cell may be as low as 0·2 ohm, and the resistance of a small wet cell as much as 1·5 ohm under normal conditions. The resistance increases as the cell is used and becomes excessive when the depolarizer is exhausted. It can be reduced slightly by arranging two or more zinc rods in parallel for the negative pole, thereby increasing the surface exposed to the electrolyte.

Post Office Type. In the cells used by the Post Office at subscribers' stations, manganese chloride is used for the electrolyte instead of sal-ammoniac.

The chemical action is then—

$$Zn + MnCl_2 = ZnCl_2 + Mn$$

in the outer cell, and

$$Mn + 3MnO_2 = 2Mn_2O_3$$

in the porous pot.

It will be noted that no gas is evolved, and the cells may therefore be sealed in an airtight box, thus preventing evaporation of the electrolyte. Indeed, if the cells are not sealed, an oxide tends to form on the zinc rod, which raises the internal resistance of the cell.

For high discharge rates, sal-ammoniac is to be preferred to manganese chloride, although with the latter, the e.m.f. is slightly higher (1·5 volts).

Amalgamation. The zinc rod is amalgamated with mercury to prevent 'local action,' or the dissolving of the zinc whilst the cell is not in use. If pure zinc could be obtained, there would be no tendency for the zinc to dissolve when a current was not being taken from the cell, but impurities in commercial zinc set up small differences of potential on its surface, currents flow in the surrounding electrolyte, and the zinc is dissolved. The addition of mercury to the zinc, whilst not interfering with the ordinary behaviour of the cell, prevents the impurities from coming into contact with the electrolyte, as only the pure zinc is dissolved by the mercury, and forms a film on the surface of the rod.

Capacity of Cells. The smallest Leclanché cell used by the Post Office has a capacity of approximately 20 ampere-hours (Ah.), and the largest 200 Ah., at a discharge rate of 50 mA., under ordinary conditions of intermittent use. The capacity is reduced considerably if the discharge rate is increased, or if the cell is in use continuously.

Connection of Cells. Primary cells may be connected—

(*a*) In *series*, in which case the total e.m.f. is the sum of the separate e.m.f.'s, and the internal resistance is the sum of the separate internal resistances.

(*b*) In parallel, when the e.m.f. is that of one cell, and the

internal resistance is the joint resistance of the separate internal resistances in parallel.

(*c*) In series-parallel.

The e.m.f. is the sum of the e.m.f.'s in series in any one of the equal parallel paths, and the internal resistance is the joint resistance of the parallel paths, the resistance of each of which is the sum of the internal resistances in series.

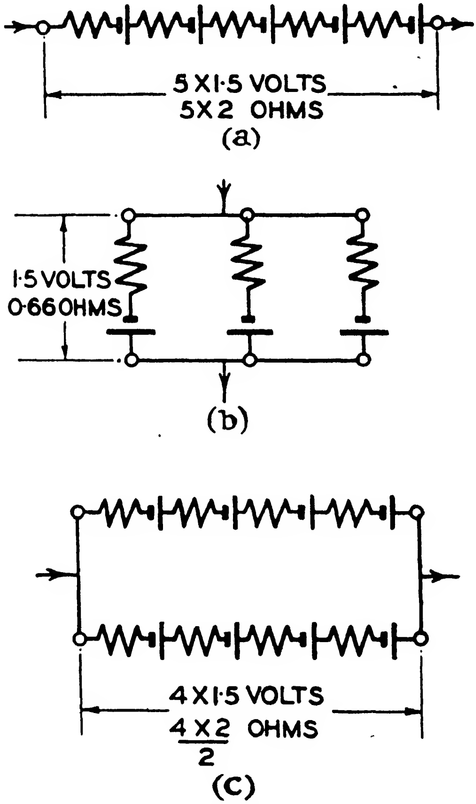


Fig. 137. Connections of Cells

Examples, using cells of e.m.f. 1·5 volts and internal resistance 2 ohms (Fig. 137).

(*a*) 5 cells in series.

$$E = 5 \times 1{\cdot}5 = 7{\cdot}5 \text{ volts.}$$

$$r = 5 \times 2 \quad = 10 \text{ ohms.}$$

(*b*) 3 cells in parallel.

$$E = 1\cdot5 \text{ volts.}$$

$$r = 2/3 = 0\cdot6 \text{ ohm.}$$

(*c*) 8 cells in series-parallel. (2 sets in parallel, each of 4 in series.)

$$E = 4 \times 1\cdot5 = 6 \text{ volts.}$$

$$r = 4 \times 2/2 = 4 \text{ ohms.}$$

It should be stressed that for any connections involving cells in parallel, the e.m.f.'s of the parallel branches must be equal, otherwise local currents will flow and upset the calculation.

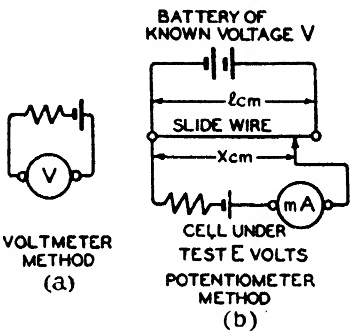


FIG. 138. TESTING VOLTAGE OF CELLS

Suitability of Primary Cells for Telephone Purposes. Owing to their tendency to polarization, Leclanché cells are not suitable for use where a continuous flow current is required. To supply transmitter current in local battery telephones, and to operate trembler bells, they are quite satisfactory, as plenty of time is allowed between discharges for the cells to recuperate. Small C.B.S. and magneto exchanges and P.B.X. switchboards may be worked from the largest size of cell, provided the output required does not exceed one ampere-hour per day.

Dry cells are used where portability is essential, e.g. in a lineman's telephone, or where the space available does not permit suitable mounting or adequate accessibility of wet cells.

Testing. The e.m.f. of a cell is measured (*a*) by connecting a high resistance voltmeter across the terminals when the cell is disconnected from any other circuit, or (*b*) by means of a potentiometer (Fig. 138).

With the potentiometer method, a known voltage is applied to the terminals of the slide wire, and the sliding contact is then moved along the wire until no current flows in the galvanometer. The e.m.f. of the cell then bears to the voltage

across the wire terminals, the same relation as the length of wire tapped to the total length—

$$\text{i.e. } E/V = x/l \text{ or } E = Vx/l \text{ volts.}$$

Internal Resistance. The internal resistance of a cell can be measured by various methods. The most usual is to connect a high resistance voltmeter across the terminals, and then note the drop in potential when a known resistance is connected in parallel. Fig. 139 gives the connections.

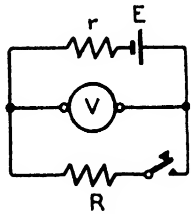


FIG. 139
INTERNAL RESISTANCE OF CELL

If E is the e.m.f. of the cell, and V the voltage across its terminals when a resistance R ohms is joined in parallel, then, drop in potential—

$$= (E - V) \text{ volts}$$

current flowing $= V/R$ amperes.

It follows from these results that if a flow of current of V/R amperes produces a drop in potential of $(E - V)$ volts, then the resistance r ohms of the rest of the circuit must be such that—

$$r = \frac{E - V}{V/R} \text{ ohms.}$$

Simplified, this becomes—

$$r = R\,(E - V)/V \text{ ohms.}$$

Current in External Circuit. When the e.m.f. and internal resistance of a battery of cells are known, the current which will be obtained in an external circuit of R ohms resistance can be calculated as follows.

Let the e.m.f. available be E volts. Then, with an internal resistance of r ohms, the total circuit resistance is $(R + r)$ ohms.

The current is, therefore—

$$I = E/(R + r) \text{ amperes.}$$

General. It has been found that the performance of a Leclanché cell is improved if a quantity of zinc chloride is added to the electrolyte. The chemical action is not changed, but the capacity is increased, and the formation of crystals retarded. To prevent the 'creeping' of the solution in unsealed cells, the tops of the jars are painted with a preparation of bitumen. The zinc rods are not cylindrical in shape, but

tapered, this form having been found to be more economical, as in service the zinc is dissolved from the thicker portion more quickly than from the tip. The depolarizing agent, manganese dioxide, is crushed as finely as possible in order to expose the greatest amount of surface to the hydrogen gas evolved in the action of the cell.

The manganese dioxide may be mixed with crushed carbon to reduce the internal resistance of the cell, and is sometimes formed into solid blocks with the aid of an adhesive agent.

SECONDARY CELLS

In all but the smallest telephone exchanges secondary cells of the lead-acid type are employed as a source of current.

The term 'secondary cell' infers that the electrical energy is stored in, rather than produced by, the cell. Chemical changes occur when the cell is 'charged' by an electric current, and reverse chemical changes take place during discharge, causing the current to flow in the opposite direction when the external circuit is completed. The cycles of charge and discharge may be repeated many hundreds of times during the life of the cell. The term 'accumulator' is sometimes used to denote a secondary cell battery.

As compared with primary cells, they have the advantages of—

(*a*) higher and more constant e.m.f. (approximately 2 volts per cell);

(*b*) much lower internal resistance (usually negligible);

(*c*) non-polarization, no matter how large a current is taken from the cell.

For telephone exchanges and repeater stations, secondary cells are utilized to provide a constant voltage battery of low resistance, this latter feature being essential when several speech circuits are connected to a common source of supply; otherwise, small changes of potential produced across the battery terminals by speech currents in one circuit would be superimposed on any parallel circuits. The result would be that overhearing would occur on all circuits in use simultaneously.

Types of Secondary Cell. There are two main types in modern usage, the *Planté,* or *formed plate* cell, and the *Faure,* or *pasted plate* type. The difference between them lies only in the

method of construction; in chemical action they are identical, and are not dissimilar in appearance. A glass tank, or wooden

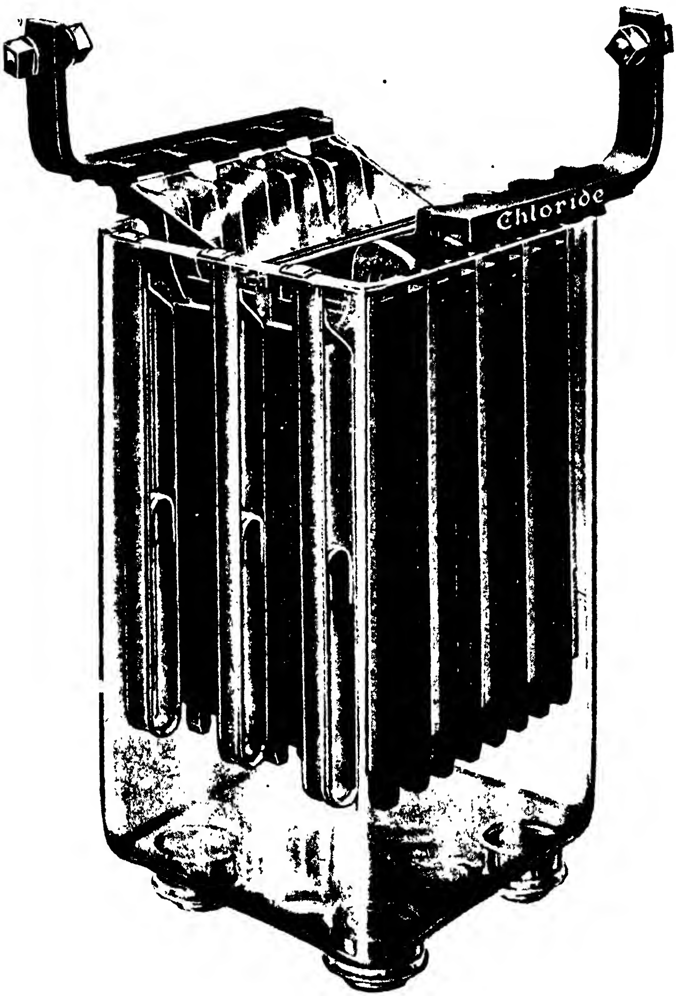


Fig. 140. Secondary Cell
(*Chloride Electrical Storage Co. Ltd.*)

box lined with lead, is used to hold the electrolyte, which is a dilute solution of sulphuric acid (H_2SO_4).

The positive and negative plates are immersed in the electrolyte, and are supported by the sides of the glass box, or where

lead lined tanks are used, by thick glass slabs. The positive and negative plates consist of lead frameworks containing the 'active material'—lead peroxide in the case of the positive, and spongy lead in the case of the negative (in the charged state).

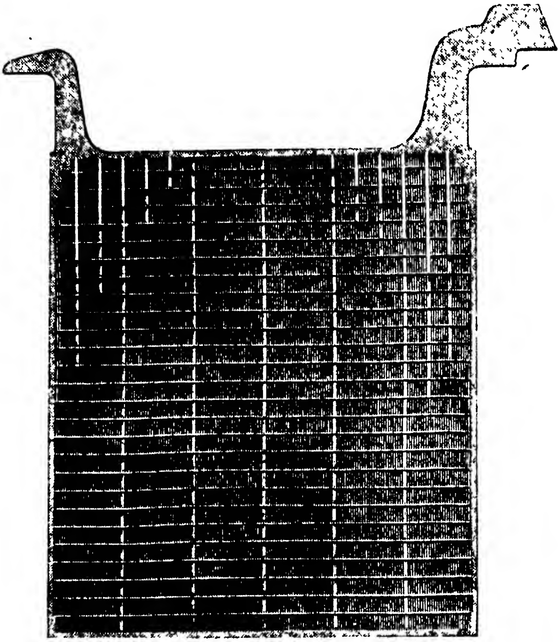


FIG. 141. PLANTÉ POSITIVE PLATE
(*Chloride Electrical Storage Co. Ltd.*)

The two methods of preparing the plates will first be examined.

Planté Process. This process is only used for positive plates. The framework of pure lead sheet, shaped as desired (see Fig. 141) is deeply grooved in order to increase its surface area, and to provide a key for holding the active material. The plate is 'formed' by the following process.

(*a*) The plate is immersed in a solution of 'forming agents' consisting of a mixture of various acids and salts. Some of these serve only to corrode the surface of lead, forming a compound of lead which is turned into lead sulphate by the sulphuric acid present in the solution. The plate is then connected to the positive terminal of a supply of electricity, the negative side of which is joined to a sheet of lead immersed in the same solution to conduct the current from it. As the current flows, the lead sulphate ($PbSO_4$) is converted into lead peroxide (PbO_2). This action proceeds until the required depth of oxide is obtained.

(*b*) The direction of current is now reversed, until the lead peroxide has all been replaced by pure spongy lead (Pb). The

object of this is to ensure that no trace of the effects of the 'forming agents' remains in the plate, as lead deposited by electrolysis is in its purest state.

(c) The plate is now washed, placed in clean dilute sulphuric

FIG. 142. PASTED POSITIVE PLATE
(Chloride Electrical Storage Co. Ltd.)

acid, and the current passed once more in the original direction. The lead peroxide, free from any trace of foreign matter, is reproduced, and the plates are said to be 'formed.'

Various devices are adopted in manufacture to secure rigidity in the plates, and different makers' products should be examined, so that the alternative forms of construction may be appreciated.

Faure Process. For the positive plates formed by this process, a lead grid is used as a framework to hold the active material, which is in the form of a paste (Fig. 142). The lead used in the grid is strengthened by the addition of a little antimony, and the active material is forced into the interstices of the framework.

The paste consists chiefly of one of the many oxides of lead, to which is added small quantities of various compounds, in order to accelerate the chemical action and assist in the setting process. Complicated mechanical methods are used to secure

the paste in the framework so that continued cycles of charging and discharging do not lead to disintegration of the plate.

Negative plates in most batteries are produced by the Faure process, but differ from the pasted positive plates in their

FIG. 143. BOX TYPE NEGATIVE
(*Chloride Electrical Storage Co. Ltd.*)

manner of construction. Each plate consists of two perforated lead trays, fitted with their open ends together, thus forming a shallow box, divided internally by a number of rectangular and horizontal ribs, which serve also to strengthen the framework (Fig. 143).

Paste is inserted into one half, and the other section is then riveted on top. The electrolyte thus has free access to the active material, which is itself held in close contact with the lead plate.

FORMING. Positive and negative Faure plates are 'formed' by immersing a pair of each in dilute sulphuric acid, and passing a charging current from the positive to the negative plate through the electrolyte.

The lead oxide (PbO) in each plate is first converted to lead sulphate ($PbSO_4$), and then on continuing the flow of current,

the lead sulphate is converted to lead peroxide (PbO_2) at the positive plate, and pure spongy lead (Pb) at the negative plate. A small amount of lead sulphate is left in each type of plate, and this amount is increased, by partially discharging the plates, if they are to be stored.

Alkaline Cells. For use as a *counter e.m.f.* cell in the parallel battery float scheme, the "Nife" alkaline accumulator is employed. Some special features of this type of cell are as follows—

(*a*) Practically zero capacity due to absence of formation of plates, allowing the cell to be short-circuited without damage.

(*b*) Even voltage characteristic, independent of the direction of the current.

(*c*) Inert and indestructible plates.

(*d*) Absence of corrosive fumes.

The construction of the cell is shown in Fig. 144 and it will be noted that the sleeve surrounding the plate assembly is perforated at the bottom to allow adequate circulation of the alkaline electrolyte, the normal specific gravity of which is 1·190. The cells are 'topped up' when required with pure distilled water.

When short-circuited, no chemical action occurs in the cell as there is no residual capacity, but the nominal terminal voltage reappears instantaneously when the cell is reinserted in the circuit. This voltage varies between 1·95 and 2·05 volts approximately over the range of current from one-half to one and a half times the rated value. The application of these cells in a charging circuit is given in Fig. 163.

The electrodes are constructed of nickel plated iron, and the electrolyte is a solution of caustic potash (Potassium hydroxide —KOH).

The plates are inert under all conditions, and the flow of current results only in the decomposition of the water in the electrolyte. This is replaced periodically when the level falls to the mark on the container, indicating that the specific gravity of the solution has risen to about 1·250.

Assembly. Secondary cells, with either Planté or Faure process plates, are assembled so that each section of the positive plate lies between two negative plates.

There is, therefore, always one more negative than positive

section, except in portable cells of the smallest dimensions, which may contain only one plate of each type.

The object of this arrangement is to ensure that both sides of each section of the positive plates are evenly utilized, since otherwise severe mechanical stresses would be set up which would cause buckling of the plates. Since, in the charged con-

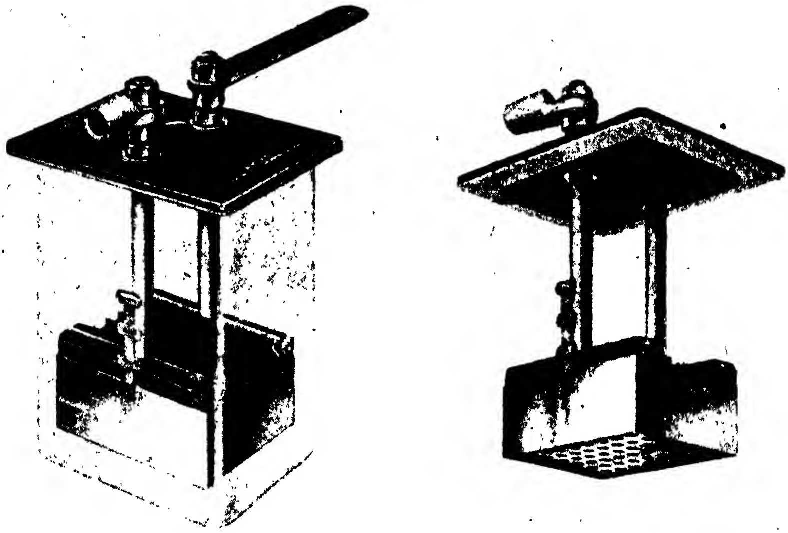


FIG. 144. "NIFE" CELL

dition, the negative plates consist of pure lead, the danger of unequal stresses is less acute. The plates are prevented from touching each other by means of *separators*, which are inserted between adjacent plates. Separators usually consist of glass tubes, which are held in position by guides in the negative plates, but wood, ebonite, or other suitable insulating materials may be used if desired.

Tubular separators rest on the bottom of the tank, but some forms may be supported from the sides, or from the plates themselves.

The various methods of preventing the plates from coming into contact can best be understood from examination of the different manufacturers' cells.

It is a general practice with stationary cells to place a thin

sheet of glass, termed a *spray-plate*, over the top of the cell, to prevent foreign matter from dropping into the electrolyte, and also so that acid spray may be trapped. The glass is slightly tilted to allow the drops of electrolyte formed by the spraying action to run back into the cell.

Fig. 145 gives a general view of two 50-volt batteries assembled in battery room at Whitehall Exchange, London.

Initial Charge. When the positive and negative plates are taken from storage and placed for the first time into the tanks, they are not in a suitable condition to be discharged without first undergoing a preliminary charge of a special nature.

The forming process leaves the negative plate consisting of pure spongy lead, which is very liable to rapid oxidization on exposure to the air. The lead oxide (PbO) thus formed on the surface of the negative plate is immediately attacked by the electrolyte when the latter is poured into the freshly set-up cells, and the sulphuric acid (H_2SO_4) dissolves the lead oxide, forming lead sulphate ($PbSO_4$) and water (H_2O).

As a result, the density or specific gravity (sp. gr.), of the electrolyte is diminished, by virtue of the chemical action which takes place at the negative plate.

Arrangements are made for the charge to commence as soon as the acid has been poured into the cells, and the passage of current from the positive to the negative plates begins to convert the lead sulphate on the negative plates back into pure lead.

Both the chemical and electrochemical actions take place simultaneously, until all the lead oxide has disappeared.

During this period, the specific gravity of the electrolyte falls steadily, due to the abstraction of the sulphion (SO_3) from the electrolyte.

As soon as the lead oxide has all been converted, the specific gravity begins to rise, and continues to do so until the end of the charge. When all the lead sulphate on the negative plate has been converted back into lead, further passage of current between the plates merely decomposes the water in the electrolyte into its constituent parts, hydrogen and oxygen. These gases are given off in the form of bubbles from the plates, and the action is termed *gassing*. The charge is stopped shortly after this phenomenon is observed.

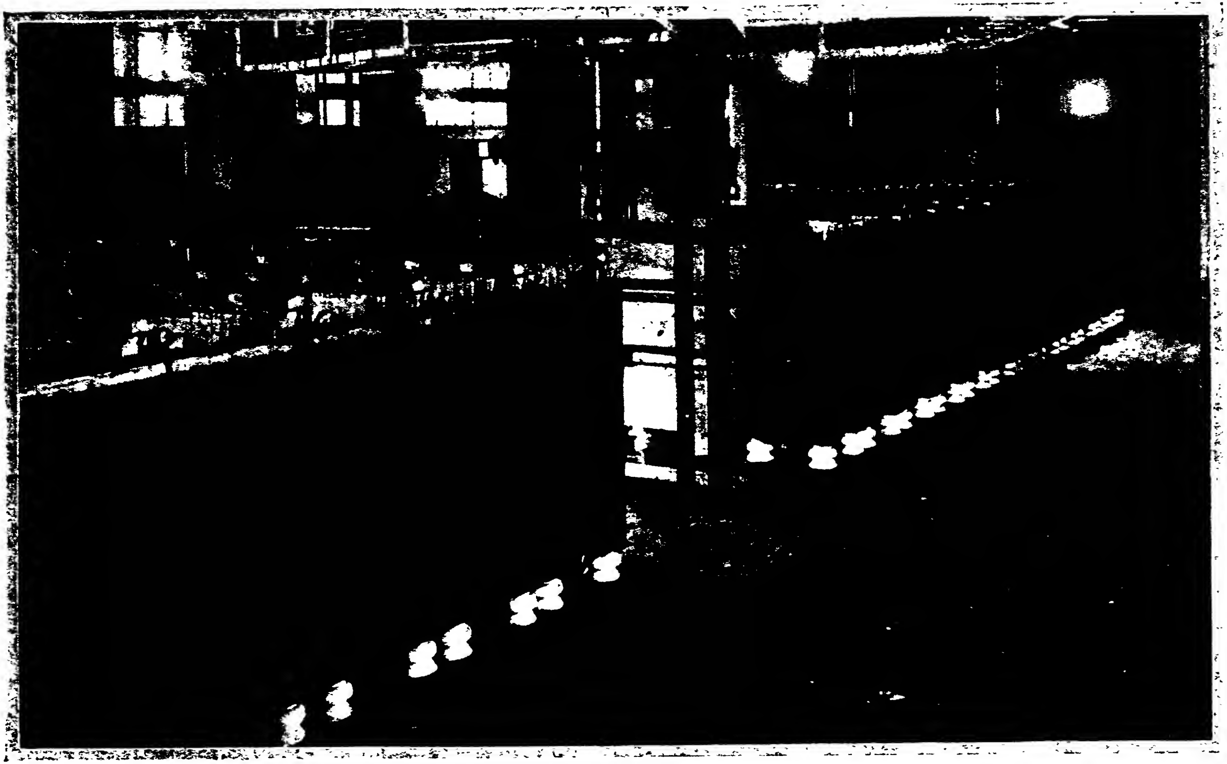


FIG. 145. BATTERY ROOM
(*Siemens Bros. & Co. Ltd.*)

Electrolyte. The e ectrolyte consists of pure sulphuric acid, diluted with distilled water until the specific gravity is about 1·215. As the specific gravity is taken as an indication of the state of the battery, the values are measured by means of a hydrometer, which is calibrated to read specific gravity values multiplied by 1 000. A reading of 1 215 divisions therefore indicates a specific gravity of 1·215, and a reading of 1 190 one of 1·190, and so on. The condition of the electrolyte will be referred to by the hydrometer readings.

When the cells are fully charged, the reading should be about 1 215 at 60° F. The specific gravity will decrease by about one-third of a division on the hydrometer for each degree rise in temperature, and increase correspondingly when the temperature falls. Hydrometer readings should therefore be corrected for temperature, before being used to estimate the residual charge in a cell for which the limits of specific gravity have previously been determined.

When a cell is fully discharged, the specific gravity of the electrolyte will have fallen to a value round about 1·170; and a test discharge on a new battery is carried out in order to determine the normal range of specific gravity of the electrolyte over a complete cycle.

To restore the specific gravity to its original value, the discharged cell is charged, i.e. a current is passed from the positive to the negative plate by the application of an external e.m.f.

The values of the specific gravity during a typical charge and discharge cycle are shown in Fig. 146.

From statistics such as these, the charge required to restore the battery to a fully charged condition may readily be assessed, as also may the residual charge of a partly discharged cell. It should be noted that the value after charging should not be recorded until the proper diffusion of the electrolyte has taken place, since the stronger electrolyte is produced near the plates, and a period of an hour or more may elapse before the density of the electrolyte is the same throughout the cell. Towards the completion of each charging operation, the gassing which takes place results in the removal of water (H_2O) from the electrolyte, and the level of liquid in the cell consequently falls, while the specific gravity increases. Distilled water is added periodically to the cells to make good the loss due to gassing

and ordinary evaporation, and the process of restoring the electrolyte to normal in this way is termed *topping up*. It should only be carried out after the cell has been fully charged.

In some situations, where open cells have to be accommodated in the same room as electrical apparatus, or other

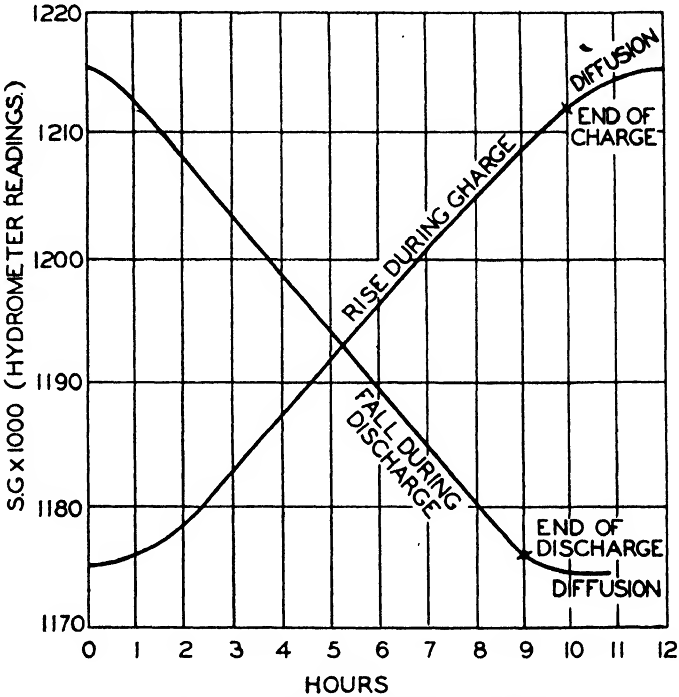


FIG. 146. VARIATION OF SPECIFIC GRAVITY

items which will suffer damage from acid fumes, it may be advantageous to place a layer of insulating oil over the surface of the electrolyte, to prevent spray and fumes from escaping into the atmosphere.

As the oil has a slightly adverse effect on the life of the plates, it should not be used except in special circumstances.

Discharging. After completion of the initial charge, the voltage of each cell will soon assume its normal value of approximately 2·05 volts, providing the specific gravity of the electrolyte has been corrected to the usual standard value of 1 215. The battery may now be connected to an external

circuit, and current taken from it until the cells are discharged, i.e. when the lead oxide on the positive plate and the pure lead of the negative plate have been converted to lead sulphate.

The average discharge current multiplied by the time of discharge indicates the number of ampere-hours that the cell has delivered. If the discharge is taken to the point where the voltage drops to round about 1·8 volts and the cell is practically exhausted, the full capacity of the cell has been obtained, and this is rated in ampere-hours.

The time taken is of importance, since it is found that a cell of, say, 100 Ah. nominal capacity can deliver this quantity of electricity if discharged in nine hours. If the time of complete discharge is decreased, the capacity will be lower, whilst if the discharge is spread over a longer period, a slightly greater capacity may be obtained.

This can be explained by the fact that the electrolyte is continually reduced in density at the point of contact with the active material of the plates, and unless sufficient time is allowed for the stronger electrolyte to penetrate to the active material, the chemical action is impeded and the capacity falls.

Normally cells should not be discharged in less than nine hours, and even over this period complete diffusion of the electrolyte is not obtained. Increasing the time to twelve or fifteen hours makes a noticeable difference to the capacity obtained, but above fifteen hours the improvement is small. The graph in Fig. 147 shows the relation between the capacity and time of discharge.

Temperature. At temperatures above normal, a cell will be found to give a greater discharge capacity, and *vice versa* for lower temperatures. A high temperature results in—

(*a*) an increase in e.m.f. of the cell;

(*b*) a reduction in internal resistance;

(*c*) an increase in rate of diffusion.

All these factors combine to permit a better output from the cell, and the extent to which improvement may be expected is shown on the graph, Fig. 148.

The chemical action during discharge may be summarized by the following chemical equation—

$$\underset{(+\text{ve})}{PbO_2} + \underset{(\text{electrolyte})}{H_2SO_4} + \underset{(-\text{ve})}{Pb} = \underset{(+\text{ve})}{PbO} + \underset{(\text{electrolyte})}{H_2O} + \underset{(-\text{ve})}{PbSO_4}.$$

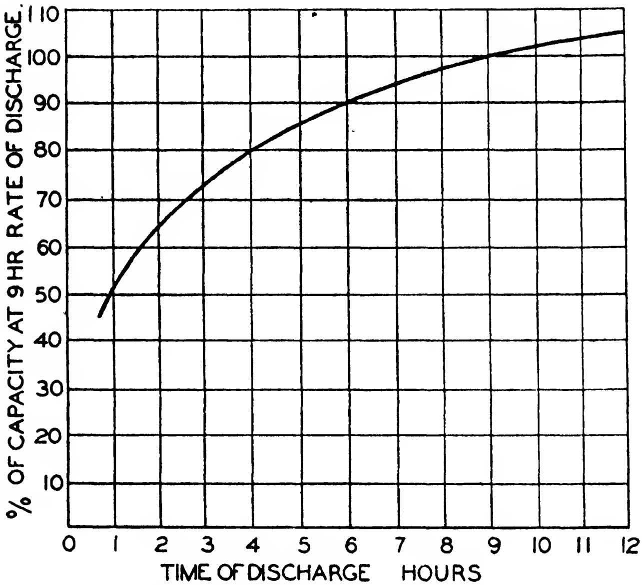


FIG. 147. VARIATION OF CAPACITY WITH TIME OF DISCHARGE

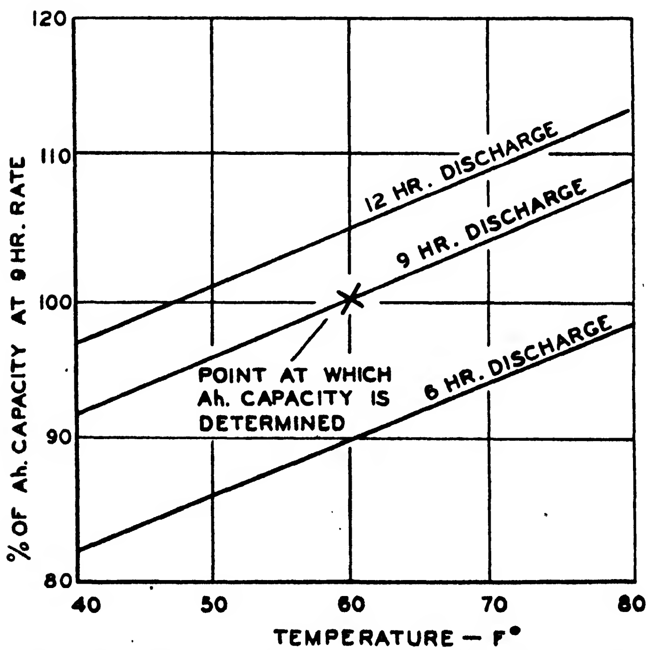


FIG. 148. RELATION BETWEEN CAPACITY AND TEMPERATURE

The PbO formed on the positive plate then combines with more H_2SO_4 to form $PbSO_4$ (lead sulphate) and water (H_2O). When both plates have all their surface converted to lead sulphate, chemical action ceases, and if the discharge circuit is not broken, the voltage will decrease to zero.

The discharge cannot be taken to the point where the electrolyte becomes pure water, since more acid than the active material of the plates can decompose is always present. The internal resistance does not therefore increase to any extent during discharge, as it would if the electrolyte became a very weak acid solution.

Charging. To restore a discharged cell to normal, it is removed from the external circuit and connected across some suitable source of e.m.f., usually a d.c. generator, or the d.c. output from a rectifier.

Current is caused to flow through the cell at such a rate that the requisite number of ampere-hours is passed back through the cell over a period of eight hours or more, thus converting the lead sulphate on the plates back into its original state.

As in the case of discharging, the current must not be too great, or the lead sulphate will not be properly decomposed. The specific gravity of the electrolyte rises steadily during the charging process, until the lead sulphate is all converted, when the rise becomes much slower. This is accounted for by the fact that 'gassing' commences, and the amount of H_2O removed from the electrolyte by this means is small, whilst no sulphuric acid is being produced by the conversion of lead sulphate to lead and its oxide. The rate of charge should be diminished during this period, since too active gassing will damage the structure of the plates.

Once every month an 'equalizing' charge is given to a battery, to ensure that all the cells have the lead sulphate fully converted. This is ascertained by continuing the ordinary charge at a reduced rate until the specific gravity of each cell has remained constant for three consecutive half-hourly readings. For ordinary purposes, the hydrometer reading of the first, or 'pilot' cell is taken as an indication of the state of the whole battery, but local discharges in individual cells, caused by partial short circuits or local action at the plates, tend to give rise to variations in residual charge throughout the battery.

After a time this state of affairs will result in some of the cells being worked at a lower specific gravity than others, and it is the function of the equalizing charge to restore all cells to normal at fixed intervals.

The chemical action during charge is exactly the reverse of that during discharge. The lead sulphate is converted back to lead peroxide at the positive plate, and to pure lead at the negative, sulphuric acid being restored to the electrolyte.

When gassing commences, the water in the electrolyte is split up into its constituent parts—

$$H_2O = H_2 + O.$$

The mixture of these gases is very inflammable, and precautions must be taken against the exposure of naked lights in the battery room.

The rise of voltage during charging, and the fall during discharging (at a constant rate) is shown in Fig. 149. In each case the internal resistance of the cell, although small, has some effect on the voltage values, as the current is high.

Capacity of Cells. Secondary cells are made in all sizes from less than 1 Ah. to 15 000 or so. The smaller cells are used for very small discharges at high voltage, e.g. anode batteries for radio receivers, whilst the larger batteries may serve several exchanges from a common busbar.

The actual capacity is determined by means of a test discharge through an artificial resistance, and it should be possible to obtain this capacity during the greater part of the life of the cells.

After repeated cycles of charge and discharge some of the active material drops off the plates and forms sludge at the bottom of the tank. The material is automatically replaced, however, by the action of the charging current on the lead grid of the plates, and space is allowed below the plates for the sludge to accumulate without causing a short circuit between the positive and negative plates.

Efficiency. The ampere-hour efficiency of a secondary cell is given by $100 \dfrac{\text{ampere-hours capacity on full discharge}}{\text{ampere-hours required for full charge}}$ per cent. The number of ampere-hours may be measured directly from a meter, or computed from a series of readings of the ammeter at

fixed intervals. A good battery will show 90 per cent or more efficiency in this respect.

The watt-hour efficiency is lower, as it takes into account the terminal voltage of the cell. It is given by the expression—

$$\text{Watt-hour efficiency} = 100 \times \frac{\text{discharge watt-hours}}{\text{charge watt-hours}} \text{ per cent.}$$

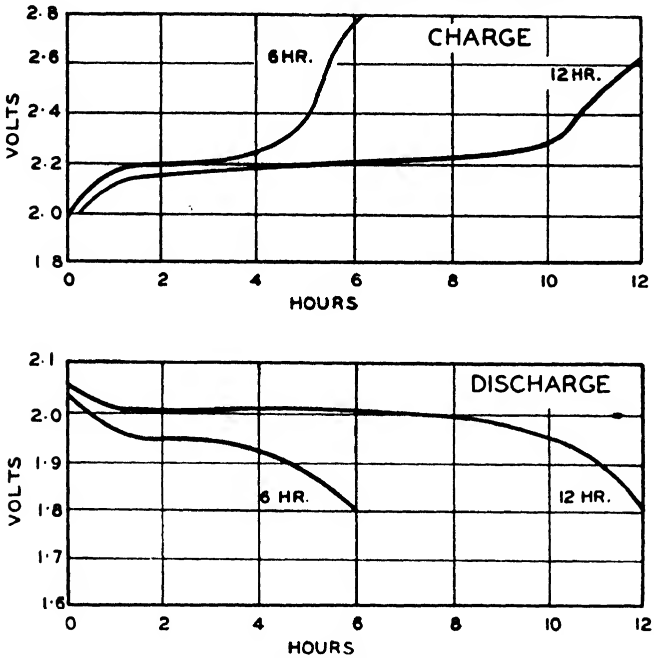


Fig. 149. Voltage of Cell during Charge and Discharge

The values may be obtained directly from a wattmeter, or calculated from a series of readings of ammeter and voltmeter. A good value is 75 per cent. It is the watt-hour efficiency, in conjunction with the efficiency of the charging machine, which determines the cost of running the batteries.

Floating. Most power switchboards for telephone batteries are arranged to permit the paralleling of one or more of the charging machines with the particular battery on discharge. This is advantageous if the discharge load of the exchange would exhaust the battery in less than twenty-four hours, or if the peak discharge is in excess of the 9-hr. rate. The charging machine is adjusted to supply only a portion of the exchange

load, otherwise the voltage of the battery would rise above the safe limit for working the exchange. The machine should not be used, however, to supply much below half its full load current, since the loss of efficiency in conversion would be serious, and would more than balance any gain due to increasing the efficiency of the battery discharge. The connections to be made for this facility are dealt with in the next chapter.

Faults. The most usual type of fault is caused by plates of opposite polarity coming into contact. This may be caused by 'buckling' or 'treeing.'

Buckling is due to uneven expansion of a plate, caused by excessive charging or discharging, or by patches of hardened sulphate preventing the even working of the active material.

Treeing results from particles of active material settling on the negative plates, and being converted to spongy lead. It usually occurs as the result of disturbing the electrolyte by excessive gassing. When the lead 'tree' thus formed touches the adjacent positive plate, an internal short circuit is formed.

In both cases, the cell discharges continuously via the short circuit, and the specific gravity of the electrolyte falls rapidly. The fault may be located by measuring the drop in potential along the individual plates, using a sensitive detector and making contact with the extreme edges of each plate in turn.

Since current is being supplied by each pair of plates in the cell to the point at which the short circuit exists, it follows that the whole of the discharge current flows through the plate thus affected, and the drop in potential will be much greater therefore on this plate. When located, the short circuit can be removed either by a *scaling stick*, if the trouble is due to treeing, or by additional separators if buckling has occurred. In extreme cases of buckling, the plates must be removed from the cell and straightened by mechanical means. When the fault has been cleared, the cell must be restored to normal by a prolonged charge, an individual cell being connected if necessary to a low voltage *booster* generator, thus avoiding the passage of the charging current through the whole of the battery.

The internal resistance of a battery is sometimes found to rise considerably. This will usually be traced to one or more of the inter-cell connections becoming corroded. The location of the fault can be determined by connecting a sensitive voltmeter

across each inter-cell connection in turn. Normally, whilst the battery is on discharge, no deflection should be obtained, but a high resistance is indicated by a reading on the instrument. The faulty connection should be scraped clean and flat or, if necessary, reburnt. All lugs and bolts should be coated with a film of petroleum jelly to withstand the attacks of acid spray.

After cells have been in use for some time, active material is gradually lost from the plates and forms sludge in the base of the tank, and the consequent conversion into lead sulphate of further lead from the plates themselves abstracts sulphuric acid from the electrolyte, and causes its specific gravity to fall. When the electrolyte is diluted to the extent that the hydrometers sink below the lowest scale reading, the specific gravity should be restored to its original value by removing a quantity and replacing it by stronger acid, of specific gravity about 1·400.

There are other causes of decrease in specific gravity of the electrolyte, the most important being *sulphation* of the plates.

If the cell is left in a discharged condition for any length of time, the lead sulphate changes in physical properties, and becomes hard and insoluble, forming greyish white patches on the plates.

The areas thus affected take no part in the subsequent working of the cell, as the active material is not exposed to the electrolyte, and consequently the latter cannot absorb so great a quantity of sulphion (SO_3) during charge.

If a low value of specific gravity is suspected to be due to sulphation, a cadmium test should be made.

Cadmium Test. A cadmium electrode can be used to determine the condition of the positive or negative plates. Cadmium is a metal which is electro-negative to both the positive and negative plates when immersed in the electrolyte, and should therefore be connected to the negative terminal of the voltmeter, the positive side of which is connected to the suspected plate. The whole battery should be brought up to a fully charged condition, and a test discharge at the 9-hr. rate should be made by means of an artificial resistance. Towards the termination of the discharge, the voltage readings between the cadmium and positive and negative plates should be taken at intervals of half an hour, and the results tabulated. With a

good battery, the cadmium voltage readings remain almost constant, but an increase in the negative reading, or a decrease in the positive reading, indicates that the negative or positive plates respectively are failing. If both phenomena are observed before the rated capacity of the battery has been obtained, the inference is that both sets of plates are failing. Some typical tables are shown below.

TYPICAL CADMIUM TEST RESULTS

Type of Failure	Cell Volts	Cadmium to Negative	Cadmium to Positive
Negative Plates, low capacity	1·9	0·20	2·10
	1·8	0·28	2·08
	1·7	0·36	2·06
	1·5	0·55	2·05
Positive Plates, low capacity	1·9	0·18	2·08
	1·8	0·18	1·98
	1·7	0·19	1·89
	1·5	0·20	1·70
Positive and Negative Plates, failing	1·9	0·18	2·08
	1·8	0·23	2·03
	1·7	0·25	1·95
	1·5	0·30	1·80

Note. The set of Plates which is of lower capacity shows the greater change in voltage.

CHAPTER IX

POWER PLANT

THE large secondary batteries used for supplying power to telephone exchanges are periodically charged from some suitable d.c. source, the most common types of charging gear being as follows.

(1) DYNAMO DRIVEN BY GAS OR OIL ENGINE. This system is used where a mains supply is not available, or is known to be unreliable.

(2) DIRECT CONNECTION TO D.C. MAINS. This system is only used where the mains voltage is low (100 volts or less), and where the annual cost of the power absorbed in the voltage dropping series resistance is less than the annual charges on suitable alternative equipment, such as a motor generator set.

(3) MOTOR-GENERATOR EQUIPMENT. This is the most widely used system. The motor is wound for direct connection to a.c. or d.c. mains of high or low voltage, and drives a d.c. generator whose output is suitable for the particular battery.

(4) A.C. MAINS RECTIFIER. This system is used for small installations where an a.c. supply is available. Having no moving parts, rectifiers are preferable for use in situations where the plant is not under constant supervision.

The rectifiers in current usage are of three types—

(*a*) Mercury arc.
(*b*) Thermionic tube.
(*c*) Copper-oxide.

The control gear differs with the type of charging plant in use. but the methods of conversion will first be considered.

GENERATORS

D.C. Generator. The d.c. generator, or dynamo, consists essentially of an armature rotating in a powerful magnetic field. The output of a generator is a function of the strength of the field, the number of conductors in series in the armature, and the speed of rotation. It is usual to vary the output by varying the strength of the field, for charging purposes, since the engine or motor which drives the generator can be designed to give

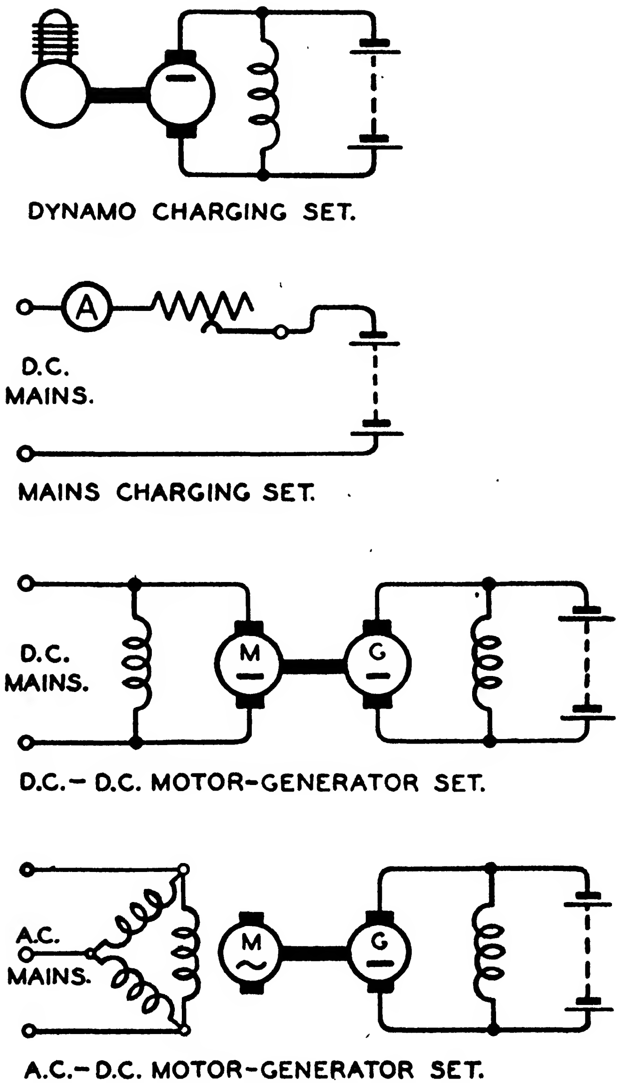


Fig. 150. Charging Sets

most economical running at one certain speed. The output in volts is given by the formula—

$$E = \frac{\text{Flux} \times \text{No. of armature conductors in series} \times \text{R.P.M.} \times \text{No. of poles} \times 10^{-8}}{60}$$

The current output obtainable is determined by the 'regulation' of the machine, i.e. the behaviour of the output voltage when the current is increased. This is in turn determined by the resistance of the armature, i.e. by the size and quantity of conductors in the winding. More turns in series give a higher voltage, but increase the resistance. In large machines several parallel paths in the armature are obtained by using more than one set of brushes, thereby reducing the resistance, and improving the regulation.

The magnetic field in which the armature rotates is provided by a winding of copper wire or strip on the pole pieces, which are provided in pairs of opposite polarity, north (N) and south (S), evenly spaced round the periphery of the tunnel in which the armature rotates. In generators used for telephone purposes, the field winding is shunt connected, as this arrangement gives a reasonably constant voltage for different output currents. Each machine is designed to meet the requirements of a particular power plant, and the main considerations are as follows.

Voltage. The voltage of the battery to be charged may be nominally 22, 24, 30, 40, or 50 volts, and a different winding will be needed for each case.

Taking a 50-volt exchange, the initial voltage of the discharged battery of 25 cells will be—

$$25 \times 1{\cdot}8 = 45 \text{ volts},$$

and the final voltage—

$$25 \times 2{\cdot}6 = 65 \text{ volts}.$$

Now, the resistance of the charging leads, switchgear, and battery may amount to 0·001 ohms. The voltage necessary to drive a current through this, will depend on the strength of the current.

If the cells are of 10 000 Ah. capacity, the maximum charging rate will be, say, 1 500 amperes.

The voltage drop in the circuit due to resistance will therefore amount to

$$1\,500 \times 0{\cdot}001 = 1{\cdot}5 \text{ volts.}$$

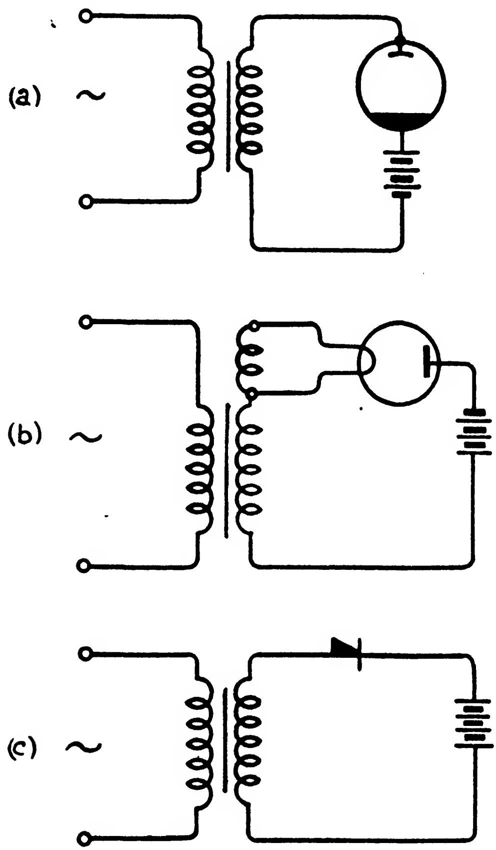


FIG. 151. RECTIFIERS
(*a*) Mercury arc. (*b*) Thermionic. (*c*) Copper oxide.

and the maximum output voltage of the machine should be

$$65 + 1{\cdot}5 = 67{\cdot}5 \text{ volts.}$$

Since the full value of charging current is no longer flowing when the voltage has reached 2·6 per cell, a maximum voltage of 60 at the machine terminals would suffice for maximum current output. The behaviour of any machine may be forecast from its performance curve, a typical example being

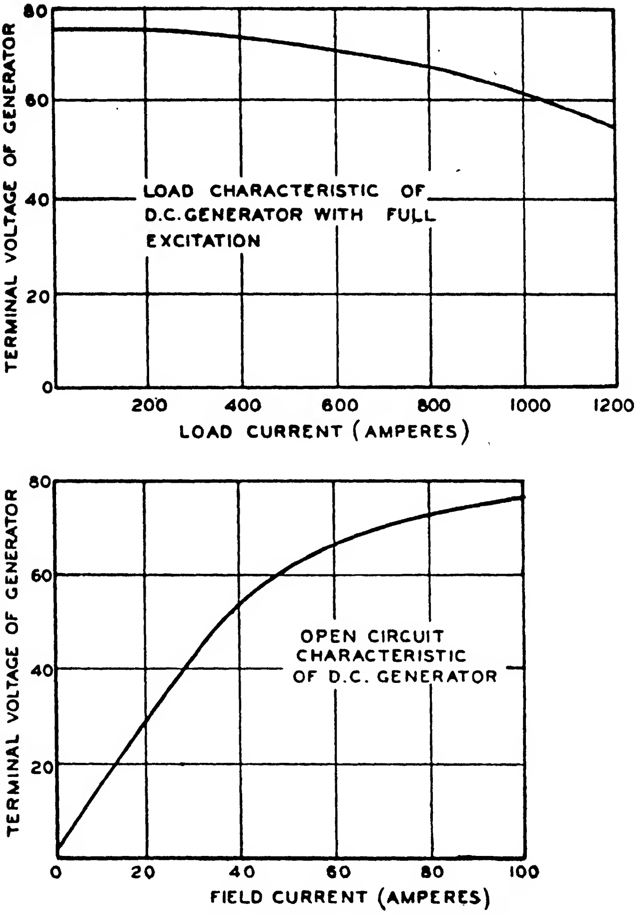


FIG. 152. D.C. GENERATOR CHARACTERISTICS

given in Fig. 152. The output of the machine in kilowatts is given by—

$$\text{kW.} = \frac{\text{Maximum volts} \times \text{Maximum current}}{1\,000}, \text{ and}$$

for the case quoted would be—

$$\frac{60 \times 1\,500}{1\,000} = 90 \text{ kW.}$$

This is known as the *rating* of the machine.

Efficiency. A generator with a rated output of 90 kW. may require another 5 kW. to energize the field, and absorb 5 kW. of power due to the copper and iron loss in the armature, and windage and friction at the bearings. Thus (90 + 5 + 5) kW. must be supplied to the machine, and its efficiency—

$$\eta_g = \frac{\text{Output}}{\text{Input}} \times 100 = \frac{\text{Output}}{\text{Output and losses}} \times 100$$

$$= \frac{90}{100} \times 100$$

$$= 90 \text{ per cent.}$$

If the same machine is used for an output of only 20 kW., the field has still to be energized, and the armature losses will not be substantially decreased. If the total loss is reduced to 9 kW.

$$\eta_g = \frac{20}{20 + 9} \times 100 = 69 \text{ per cent.}$$

It can be seen that generators should be run to give their maximum output in order to obtain the greatest economy. The power supplied to the generator shaft from the motor or prime mover is utilized partly to overcome the mechanical and electrical losses, and partly to produce electrical energy. As the shunt wound motor is a constant speed machine, it follows that the mechanical losses are almost constant and, therefore, the larger the electrical output, the better is the ratio of output/input power, and the higher the efficiency.

It is largely for this reason that exchanges are not supplied with power entirely from generators, since during the slack periods the machines would be running at very low outputs. A further difficulty is the noise produced by the commutator of a generator. This noise consists of a high-pitched hum superimposed on the direct current output, and expensive choke coils have to be employed to reduce its intensity.

Regulation of Output. The current output from the generator can be increased by increasing the terminal voltage, provided the load remains constant. The greater difference in e.m.f. thereby produced between the terminals of the machine and the cells causes a greater charging current to flow in the circuit. The generator voltage is raised by increasing the field magnetizing current. This is controlled by a series rheostat, connected

as shown in the diagram (Fig. 153). As the voltage is raised and the current increased, the load on the generator is increased, and more power must be supplied from the driving source. If an engine is employed, the momentary reduction in speed as

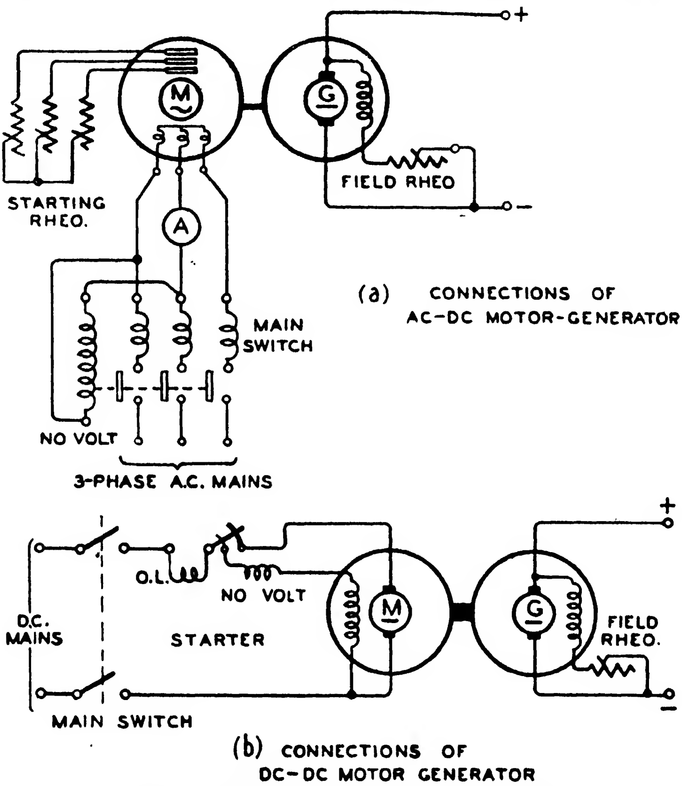


FIG. 153. MOTOR GENERATOR CONNECTIONS

the load comes on, causes the governor to function and admit more steam or fuel. The power increases until the speed returns to its original value, when the governor again functions and prevents any further increase in speed. If, as is usually the case, an electric motor drives the generator, the tendency for the speed to drop is counteracted by the resultant falling off in armature e.m.f. allowing a greater current to flow from the mains. A higher power input is thus obtained, and the motor produces a greater torque to overcome the increased resistance of the generator.

MOTORS

D.C. Motor. This machine is similar in construction to the generator, but functions in the reverse way. The armature and field windings are connected in parallel (in the case of the shunt wound machine), and joined across the power supply mains. The current which flows in the field winding produces a permanent flux, and that which flows in the armature creates a magnetic field therein which, by attraction, causes continuous rotation of the armature. The rotation of the armature in the permanent magnetic field produces a 'back-e.m.f.' in its winding, which opposes the e.m.f. of the mains. The current which flows in the armature circuit is due to the small difference between the applied and back-e.m.f.'s, which may be only 1 per cent or 2 per cent of the applied voltage at light loads. However, as the armature resistance is only a fraction of an ohm, large currents flow, and cause the rotation of the armature at such a speed that the back-e.m.f. rises and maintains the current at a value determined solely by the load on the motor.

Taking the case of a 100 kW. motor, suitable for driving the 90 kW. generator referred to earlier, the mains voltage will be, say, 500 volts, and for 100 kW. the armature current would be about 200 amperes. The field current will be about 5 per cent of this value, or 10 amperes. Taking the armature resistance as 0·125 ohms, the potential drop in the armature will be $200 \times 0{\cdot}125 = 25$ volts.

It can now be seen that if the voltage applied to the armature is 500, and the voltage drop due to the copper loss is 25, then the back-e.m.f. must account for the remaining 475 volts. Now with a constant field flux, the back-e.m.f. is directly proportional to the speed, and the design of the armature is such that the speed corresponding to the required back-e.m.f. is a suitable one for driving the generator.

Assuming, for example, that the speed in this case is 475 r.p.m., there is 1 volt back-e.m.f. for every revolution per minute. Suppose now the load were reduced to half, and the armature current fell to 100 amperes. The drop in the armature would decrease to $100 \times 0{\cdot}125 = 12{\cdot}5$ volts, and the back-e.m.f. would rise to $(500 - 12{\cdot}5) = 487{\cdot}5$ volts. It is clear that the speed must now increase to 487·5 r.p.m. to produce this back-e.m.f. There is, therefore, a change in speed of only

$\left(\frac{487 \cdot 5 - 475}{475}\right) \times 100 = 2 \cdot 6$ per cent between half load and full load, and such a performance is characteristic of the shunt wound motor. It is most suitable for driving a charging generator, since the voltage of the latter will be controlled solely by the field rheostat. In the example quoted, the efficiency of the motor was given by—

$$\eta_m = \frac{\text{Output}}{\text{Output} + \text{losses}} \times 100 = \frac{\text{Output}}{\text{Input}}$$

$$= \frac{200 \times 475}{210 \times 500} \times 100 \quad \begin{array}{c}\text{(since input current is armature}\\ \text{current + field current)}\end{array}$$

$$= 90 \text{ per cent.}$$

The overall efficiency of the converter machinery will therefore be—

$$\eta_{m.g.} = \frac{90 \times 90}{100}$$

$$= 81 \text{ per cent.}$$

An overall efficiency of 80 per cent in the converter is a satisfactory value to obtain, but can only be reached when the set is worked to full capacity.

The d.c. motor is easily started by connecting the armature to the mains via a stepped resistance, the armature current being allowed to rise to roughly its full load value on each step, when the arm is moved over to the next, and so on until a direct connection across the mains is established. 'No-volt' and 'overload' releases ensure the disconnection of the machine from the mains if the supply fails momentarily, or if the machine becomes overloaded.

A.C. Motors. The use of a.c. mains for the supply of power is rapidly increasing, and the outputs and efficiencies of a.c. and d.c. motors are roughly similar. As no commutators are ordinarily needed, the a.c. motor construction is more robust, and there are two main types in use for three-phase supplies—the *induction* motor and the *synchronous* motor. The treatment of these machines is beyond the scope of this book, but their main characteristics are as follows.

Induction Motor. The speed-torque relation for this machine is complicated, but provided that the load never exceeds twice

the normal full load, the speed will decrease slightly with an increase in load, as in the d.c. shunt motor. Beyond a certain load, the induction motor armature will 'pull out,' i.e. it will suddenly stop, and will not restart until the load is removed. For telephone purposes, induction motors must be designed to have less than 10 per cent speed variation over the possible range of loading. The maximum speed, reached at no-load, is the 'synchronous speed,' and is given by the expression—

$$\text{R.p.m.} = \frac{2 \times \text{frequency of supply} \times 60}{\text{No. of poles per phase}}$$

For a four-pole machine on 50-cycle mains this gives a speed of 1 500 r.p.m., and for an eight-pole machine, 750 r.p.m. The usual method of starting an induction motor is to insert external resistance in series with the *rotor* (or armature) windings, via *slip-rings*. By this means, heavy induced currents in the rotor whilst stationary are avoided, and as the machine gathers speed, resistance is cut out, finally leaving the rotor windings short-circuited on themselves.

Synchronous Motor. The synchronous motor is an alternator run as a motor. The d.c. field winding is usually formed on the rotating armature (rotor), the *stator* being wound with coils connected direct to the three-phase line. This avoids the connection of high voltage a.c. through brushes and slip-rings. Since the rotor has a definite fixed polarity, the speed of rotation is absolutely constant, as the field of the rotor must always be in step with the rotating field on the stator.

This constancy of speed independent of the load is a useful feature, and the synchronous speed is given by the same formula as for the induction motor.

This machine is only suitable for large outputs, however, as a separate *exciter* must be provided to produce the d.c. for the field winding. This exciter consists of a small d.c. generator coupled to the motor shaft. For large installations, the scheme offers the advantage that by suitably increasing the field current, the motor can take a 'leading' current from the mains, and thereby avoid the losses inherent with the bad power factor of the induction motor. There is the 'pull out' characteristic with this machine as well, since it must either run at synchronous speed, or not at all. The synchronous motor may

be started as an induction motor, and run up to synchronous speed by means of a *damper* winding embedded in the rotor. This damper winding also corrects 'swinging' of the rotor due to sudden changes in load.

The use of rectifiers on a.c. mains supplies provides a convenient and simple means of converting to d.c. without the use of rotating machinery, and three types are in current usage, as follows.

Mercury Arc Rectifier. The rectifier proper consists of a vacuum chamber made of glass (or in larger types, steel) into which is introduced a pool of mercury. This forms the cathode, and above it is situated an iron anode (or anodes). An arc is started between the mercury pool and an *ignition* electrode, by allowing the two to come momentarily into contact while an external voltage is applied. When the ignition anode is separated from the surface of the mercury, an arc is struck, which causes a white-hot spot to appear on the surface of the mercury. If the alternating potential it is desired to rectify is now connected between the main anodes and cathode, the arc will extend the whole distance between them, the mercury being vaporized by the heat produced at the cathode. The peculiarity of arc is that current can flow only in one direction, from the anode to the cathode, and the arc therefore acts as a rectifier. A luminous column appears in the glass container, and an intense light is emitted from the white hot cathode. Such an arc is a very efficient rectifier, and is easily started, the ignition anode being brought into momentary contact with the mercury by the use of a magnet. Once started, the arc will continue to function so long as the external circuit allows an appreciable current to flow. Since it may be desirable to disconnect the circuit without extinguishing the arc, one or more *excitation* anodes are fitted, and are connected so that an arc is formed to each as long as the a.c. is switched on, with the external circuit open. Fig. 154 shows the simplified arrangements.

When the external circuit is closed, the arc transfers to the main anodes, reverting to the excitation anodes when the load is taken off.

A reactance is inserted in series with one of the rectifier leads, to smooth out the peak voltage of the rectified half-cycles.

Although the efficiency of the arc itself may be as high as 90 per cent at high voltages, the overall efficiency of the rectifier set at full load is from 60 to 65 per cent.

Thermionic Tube (' Tungar ' Pattern). This type of rectifier functions as a two-electrode thermionic valve (diode). The cathode consists of a tungsten wire filament, heated by an electric current, and the anode is a graphite disc (Fig. 158).

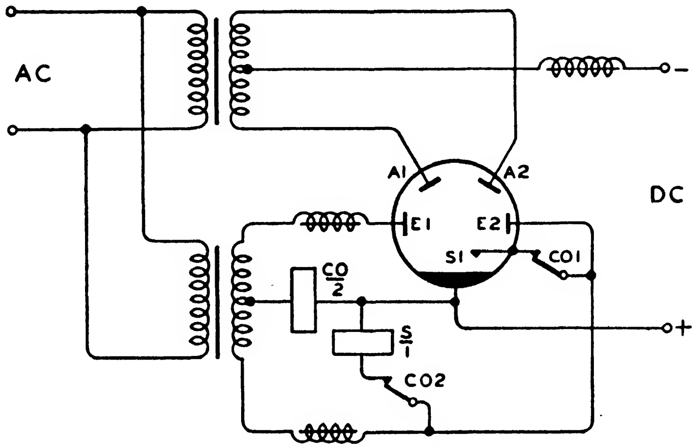


FIG. 154. CONNECTIONS OF MERCURY ARC RECTIFIER

A_1 A_2, main anodes. E_1, E_2 excitation anodes. S_1, starting or ignition electrode.

The two electrodes are supported in a glass tube, which is then exhausted of air, and a small quantity of argon gas introduced, to improve the conductance of the valve without allowing the electrodes to be consumed.

When the filament is heated and an a.c. supply is connected across the electrodes, current passes only in one direction, from the anode to the cathode, and the tube acts as a half-wave rectifier. Two tubes may be used, in a suitable circuit, for full wave rectification.

In the scheme usually adopted for small charging plants, a tapped transformer supplies both cathodes and anodes, and the tappings permit the output to be controlled. A reactance is inserted in the positive lead to the battery, to smooth out each half-cycle. In the diagram (Fig. 155), an ammeter is shown in each anode circuit so that each tube may be allowed to carry its share of the total d.c. output.

The efficiency is not quite so high as in the case of the mercury arc rectifier, as the voltage drop in the tubes is considerable, and power is being expended in heating the filaments. An average value for the overall efficiency is 60 per cent.

There are other thermionic rectifiers similar to the 'Tungar,' utilizing coated cathodes and different inert gases, but the

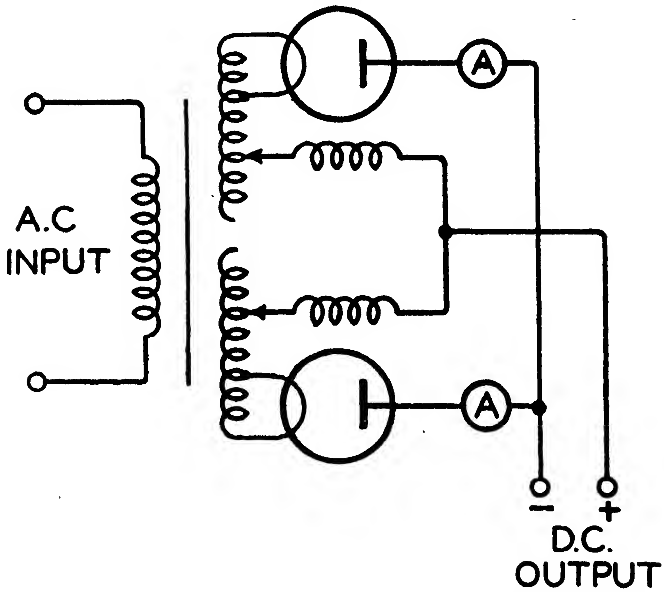


FIG. 155. CONNECTIONS OF THERMIONIC TUBE RECTIFIER

principle of operation remains the same, and their performance is very similar.

Copper-oxide Rectifier. This type of rectifier, usually called 'metal rectifier,' is frequently used for telephonic purposes, the smallest sizes being suitable for currents of a few milliamperes at one or two volts pressure, and the largest for currents of hundreds of amperes. Its rectifying action depends on the unidirectional conductivity of a film of copper oxide formed on a copper surface, and held in contact with the surface of another conductor, such as lead. The simplified connections of a single phase rectifier are shown in Fig. 156 with the volt-ampere efficiency curve.

The current flows easily from the oxide to copper, but not in the reverse direction.

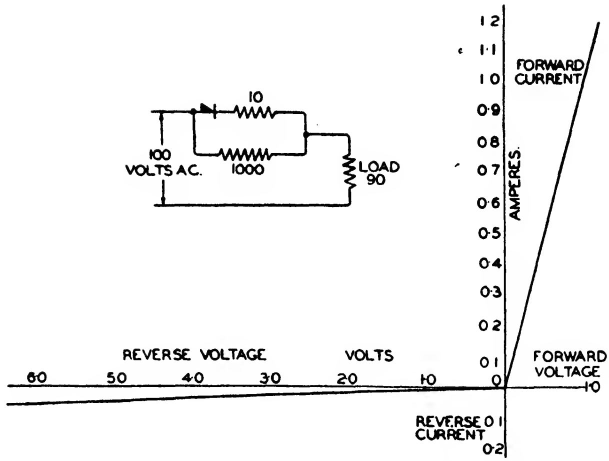


FIG. 156. CHARACTERISTIC AND EQUIVALENT CIRCUIT FOR SINGLE PHASE HALF-WAVE RECTIFIER

Loss during conducting half-cycle = $(1)^2 \times 10 = 10$ watts.
Loss during non-conducting half-cycle = $(0{\cdot}1)^2 \times 1\,000 = 10$ watts.

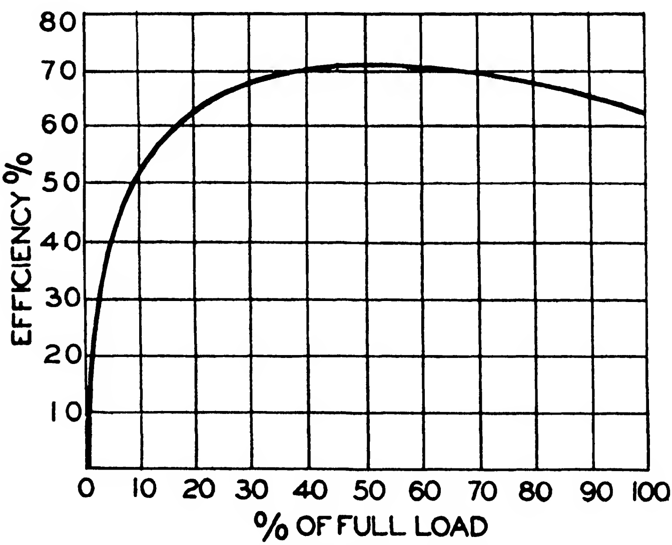


FIG. 157. VOLT-AMPERE EFFICIENCY OF METAL RECTIFIER SET
Single phase.

There is a more pronounced 'back current' with this type of rectifier than with those previously described, but it is never large enough to cause any difficulties in operation. The copper oxide rectifier has the advantage of not requiring any exciting current, and has a long life, but occupies more space than the mercury arc or thermionic type.

It is very suitable for small installations or where 'trickle charging' is adopted, but can be used for any size of power plant if desired. The connections of a full wave rectifier equipment are shown in Fig. 164.

The overall efficiency of rectifier sets for telephone purposes, utilizing copper oxide rectifiers, is 50 to 75 per cent.

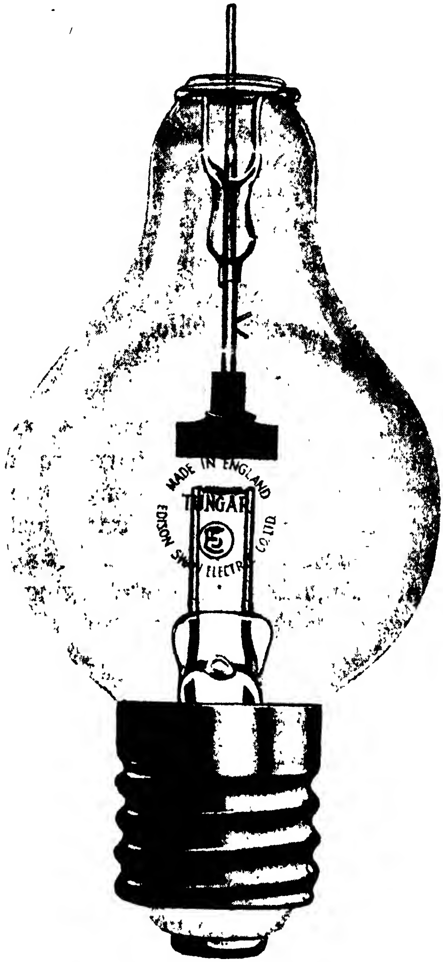


FIG. 158. 'TUNGAR' RECTIFIER
(*Edison Swan Electric Co. Ltd.*)

CONTROL EQUIPMENT

The d.c. output from all the sources described above is connected to the batteries to be charged, or in some circumstances to the exchange, via a series of switches and protective devices.

The most important of these is the device for cutting off the charge should the d.c. supply be interrupted or fall below the minimum voltage required.

Circuit-Breaker. This is inserted in the main charging lead, and consists of a heavy duty switch with a trip action. The

switch is closed by hand and completes the charging circuit via a series winding on the tripping solenoid. If the charging current exceeds a certain value, therefore, the switch is tripped, and the circuit is disconnected. A further safeguard is necessary in the event of the charging supply voltage falling below that of the battery. In such a case, the direction of the current is reversed, and the battery would discharge through the generator, running it as a motor. Some form of polarized relay is therefore fitted to the circuit-breaker so that if the direction of current changes, the polarized relay is operated, and closes the circuit of a second coil on the tripping solenoid, breaking the circuit as before. There are many different types of circuit-breaker, most of which have an adjustable setting for the overload tripping magnet. In the largest installations, circuit-breakers with time lags may be inserted in the main battery leads, adjacent to the batteries, so that in the event of a prolonged short circuit the battery is disconnected. They may be preferred to fuses in such circumstances, since the delay period is controllable, and little time is lost in reconnecting the circuit.

Switches. Knife-edge switches are generally used to effect the connections between the charging machines and the batteries. Large contact areas are employed to reduce the voltage drop, and the switch used to connect the exchange busbars to either battery is of the 'make-before-break' pattern, to safeguard against a momentary disconnection of the exchange.

Fuses. Main fuses are invariably of the enclosed cartridge type, with a fusing current equal to twice the rated current.

Alarm fuses, of the spring bead type, are connected in parallel with the main fuses, and ring the alarms when the main fuses operate.

Charging Circuit—Double Battery Charge-Discharge System. Where two main batteries are installed, and 'floating' (*q.v.*) is not necessary except under peak load conditions, the connections of the charging circuit for a 40-volt common battery exchange, and for a 50-volt automatic exchange, are shown in Fig. 159. It will be noted that either battery can be connected to either generator, but that neither the generators nor the batteries can be connected in parallel, except during the transit of the discharge switch, which has a make-break action to avoid disconnection of the exchange when changing from one

battery to the other. A voltmeter and ammeter are fitted on the power board, and can be connected, by means of a rotary switch, to any of the points marked *V*, and *A*, respectively. Where a 50-volt 'positive' or 'booster' battery is required, this is connected as shown in Fig. 165. As this battery normally has its negative terminal earthed, it must be completely isolated from the distribution before being connected to the

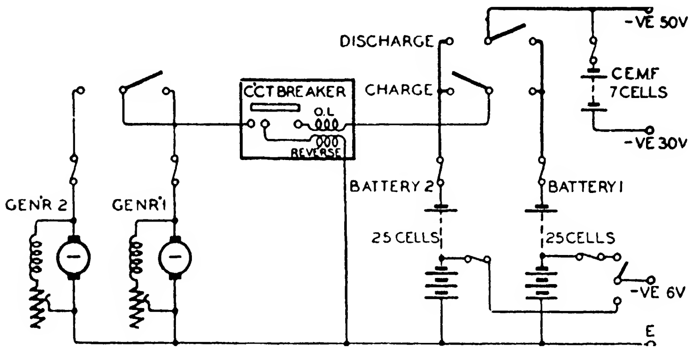


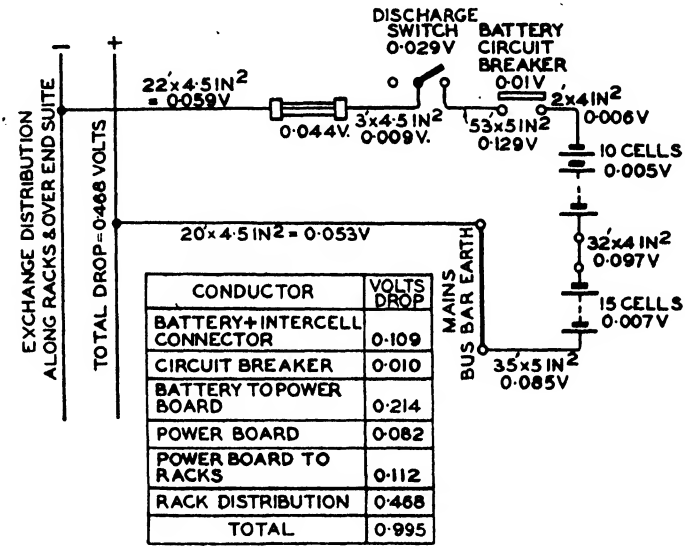
FIG. 159. CHARGE-DISCHARGE POWER CIRCUIT

charging source. It will be noted that the main batteries have their positive terminals earthed directly to the common earth busbar. Since the generators are also earthed, this obviates the need for switching both conductors in the charging circuit, and simplifies the installation considerably.

The positive terminal of the main battery is earthed at all exchanges so as to obtain uniformity in signalling over junctions, with earth and battery connections. With negative potential on the line conductors, earth faults are not masked by chemical deposits on the conductors, forming insulating films at the point of contact with the earthed object, as would be the case with positive polarity, and such faults are therefore rapidly brought to light. The main positive busbar is earthed via the M.D.F., to which the main exchange earth is connected. It is essential that the main earth be of low resistance, since otherwise, in the event of the current to earth reaching a high value, there would be a considerable drop of potential in the earth lead, and signalling to and from the exchange would be completely upset. It is usual to allow for

7 volts earth potential difference when considering signalling requirements between exchanges.

Voltage Range. No definite limits are set for the voltage at C.B. exchanges, but on 50-volt automatic systems an alarm meter is fitted, to indicate when the voltage falls below 46 or above 52. The automatic switches are designed to work between these limits, and may fail if they are exceeded.



CONDUCTOR	VOLTS DROP
BATTERY+INTERCELL CONNECTOR	0·109
CIRCUIT BREAKER	0·010
BATTERY TO POWER BOARD	0·214
POWER BOARD	0·082
POWER BOARD TO RACKS	0·112
RACK DISTRIBUTION	0·468
TOTAL	0·995

FIG. 160. TYPICAL VOLTAGE DROP DIAGRAM—DISCHARGE: 1 500 AMPERES
Length and cross-section of leads shown for typical case.

Discharge Leads. It is usual to stipulate that the discharge leads to any part of the exchange equipment shall be of such dimensions that with the maximum load the voltage drop to any point does not exceed one volt. From the main busbars, the discharge leads are taken in pairs (positive and negative) to the various racks, via intermediate distributing points, where distribution fuses are fitted. Thus the voltage drop to any particular rack may consist of the drop in the leads to the distribution point, due to the current consumed on that rack only, plus the drop between the distribution point and the main busbars, due to the whole current carried between those points. Given a knowledge of the currents required for the operation of the various portions of the equipment, and the

maximum number of circuits likely to be in use simultaneously, the voltage drop can be calculated if the resistance of the leads, in ohms per yard, is known. Distribution leads may consist of insulated cables, or of copper rods (or bars) carried on insulating supports fixed to the racks. Fig. 160 gives a typical voltage drop schedule for an exchange distribution, an example of the latter being shown in Fig. 161.

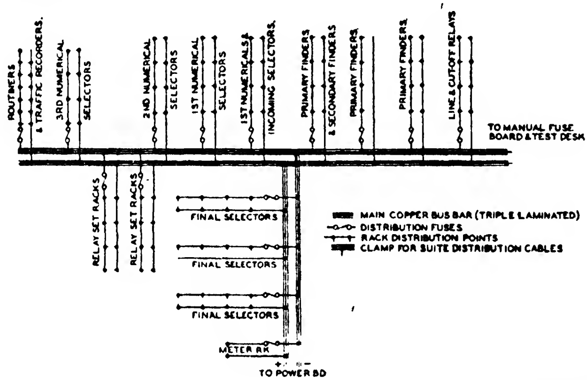


FIG. 161. TYPICAL POWER DISTRIBUTION AUTOMATIC EXCHANGE
Non-director.

Floating Systems. The charge-discharge system of supplying power to telephone exchanges has the advantages of simplicity of operation, large reserve capacity, and ease of maintaining constant voltage. It is uneconomical, however, for the following reasons—

(*a*) The large duplicate batteries occupy valuable floor space, and only 50 per cent of the installation is in use at any given time.

(*b*) The life of the plates is limited to a certain number of cycles of charge and discharge.

(*c*) The charging machine must be of such a size that it will fully charge the battery in a day.

(*d*) The charging machine must be provided in duplicate, to safeguard against mechanical breakdown.

(*e*) The overall efficiency of conversion seldom exceeds 60 per cent.

New power plants are being installed on a floating basis to overcome these drawbacks.

If the charging source is permanently connected across the

battery which is serving the exchange, the battery is said to 'float.' During periods of high discharge, both the generator and the battery supply the exchange, but as the load diminishes, the current from the generator flows into the battery, and the charging rate can be adjusted so that the battery is nearly always fully charged. With this scheme, as the amount of charge taken out of the battery is never so great as with the charge-discharge system, a much smaller battery and generator may be used.

It has already been demonstrated that a generator works more efficiently when run at full load, and in the largest floating installations, as many as four generators are provided, one large and three smaller. Connected in parallel, they can meet the greatest demand on the exchange, and the number can be reduced as the load diminishes. The problem of spare machines and emergency charging plant is thereby simplified.

In smaller installations, two generators (or rectifiers) suffice, and the charging is controlled automatically by contacts on an ampere-hour meter connected in the battery lead.

Reserve battery capacity for twelve hours only is provided, and a portable emergency power plant is employed to serve when a power supply failure exceeds this period.

The batteries are provided in duplicate, so that maintenance or renewals can be carried out without interruption to the service. The elimination of the continuous cycles of charge and discharge avoids disintegration of the plates, and maintenance is much reduced.

Whenever a generator is connected to the exchange busbars, some form of choke or filter must be employed to reduce the noise which would otherwise be produced in telephone circuits, due to the minute variations in voltage caused by the commutator on the generator. Choke coils, which must carry the full load current without saturation, are large, heavy, and expensive, so that there is now a tendency to use filters, tuned to reduce the alternating component of the charging current to a negligible value. The trouble is most marked when rectifier equipments are used.

Divided Battery Float System. This system is used for large automatic or trunk exchanges when the daily load exceeds 2 000 Ah. The outline circuit, excluding the alarm and meter

battery connections, is shown in Fig. 162. The connection of the main and C.E.M.F. batteries, and of the charging generator, is the same as in the charge-discharge scheme. A trickle-charger (a.c.-d.c. rectifier, or d.c.-d.c. dynamotor) is permanently connected across that battery not serving the exchange, thus maintaining it fully charged.

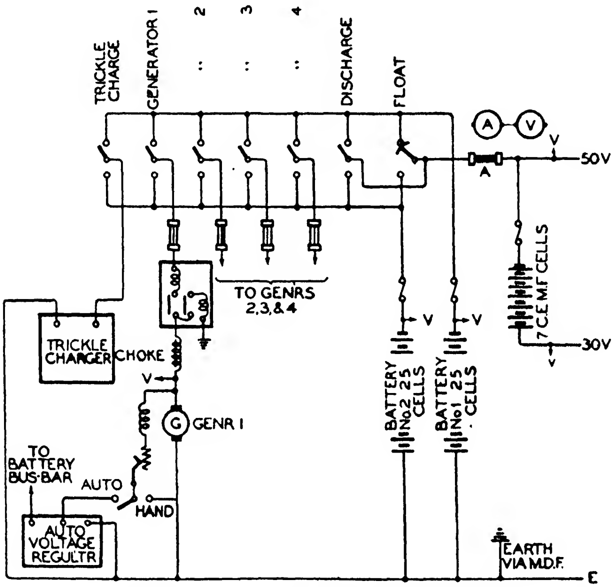


FIG. 162. DIVIDED BATTERY FLOAT SYSTEM
50 volts.

The busbar voltage is maintained between close limits (50·5 to 51·75 volts) by means of an automatic voltage regulator connected in the generator field magnet circuit. This permits the machine to vary its output according to the load on the exchange. If any of the smaller machines are connected in parallel, they are hand regulated to take a fixed proportion of the load, the variation being catered for by the large machine.

Twenty-five cell batteries are used, so that charge-discharge working may be employed in an emergency.

Parallel Battery Float System (Fig. 163). This is installed where the daily load is between 100 and 2 000 Ah. per day. Two 25-cell batteries are employed, but are connected permanently in parallel. Since they are charged in parallel, the

voltage is equalized at all stages, and there is no tendency for circulating currents to flow. An ampere-hour meter is joined directly in series, and is fitted with contacts to control the charging. A small trickle-charger is connected permanently in parallel when the main supply is a.c. When only d.c. is available, it would not be economical to run a small dynamotor continuously, and a small permanent load is connected across the

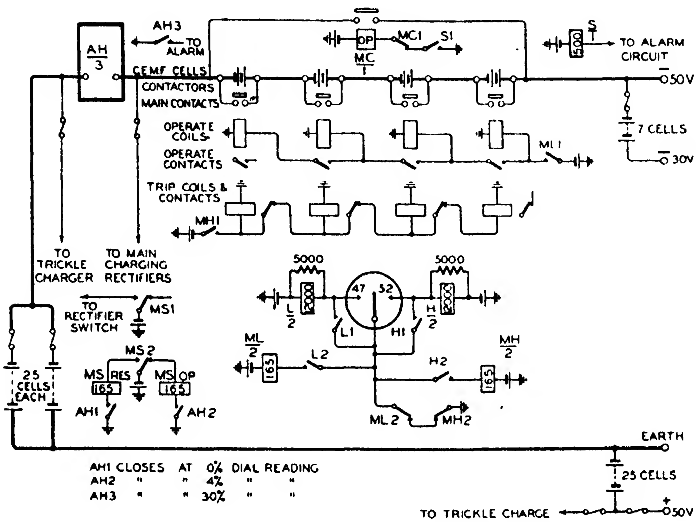


Fig. 163. Parallel Battery Float System

exchange busbars, so that leakage losses, normally too small to actuate the ampere-hour meter, are increased to a value that will ensure their registration, and subsequent compensation by an increased charge from the generator.

The latter is controlled from an automatic starter, and is switched into service when the ampere-hour meter registers 5 per cent discharge of the batteries. When the needle has returned to zero (indicating that the cells are now fully charged), the generator is disconnected, and shut down. This switching action, and other heavy current connections, is performed by contacts of mercury relays (*q.v.*), whose functions are detailed in the diagram. Constancy of voltage at the exchange busbars is ensured by a system of contactors, which insert or cut out (by short-circuiting) counter-e.m.f. cells as

required. The counter-e.m.f. cells are of a special nickel-iron-alkaline type, which have a negligible capacity, and therefore may be short-circuited with impunity. When connected in opposition to the main battery, their voltage rapidly rises to about 1·9 volts per cell, reducing the busbar voltage by this amount.

A contact voltmeter is connected across the busbars, and if the voltage rises too high (above 52 volts) relay H is operated, which in turn energizes the mercury relay MH. $MH1$ makes, and then breaks 5 sec. after MH has restored (due to the holding circuit being broken at $MH2$). During this 5 sec., the trip coil of the first of the four contactors (assuming all are operated) is energized, the contactor trips, and the two counter-e.m.f. cells are inserted in opposition to the main battery.

As the local contacts of the contactor do not close until 10 sec. after the main contacts, only one contactor is tripped on each operation of H. Subsequent operations of H, if the voltage continues to rise, trip the other three contactors.

When, due to an increasing load, the exchange voltage drops to 47 volts (allowing 1 volt maximum voltage drop in the distribution), L operates, and energizes ML. $ML1$ closes the operating circuit for the contactor last tripped (also, incidentally, for any already operated), and thereby cuts out two counter-e.m.f. cells, allowing the busbar voltage to increase. Variations of voltage in either direction are thus compensated for by the automatic switching of the counter-e.m.f. cells, and the charging proceeds under the control of the ampere-hour meter only.

In the event of the automatic switching failing, or proving inadequate to compensate for voltage change, an urgent alarm is given, and a master contactor operated (via $S1$) to cut out the intermediate contactors, and apply the main battery direct to the exchange. This contactor, once operated, must be reset by hand, thus ensuring that attention is given to the defect.

With d.c. mains, two motor generator sets are provided for charging purposes, but where a.c. is available, two or three rectifiers are installed, and are switched into use by the MS relay under control of the ampere-hour meter (Fig. 164), and no automatic starter is necessary in these cases. A permanent trickle-charge is given, which does not pass through the ampere-hour meter.

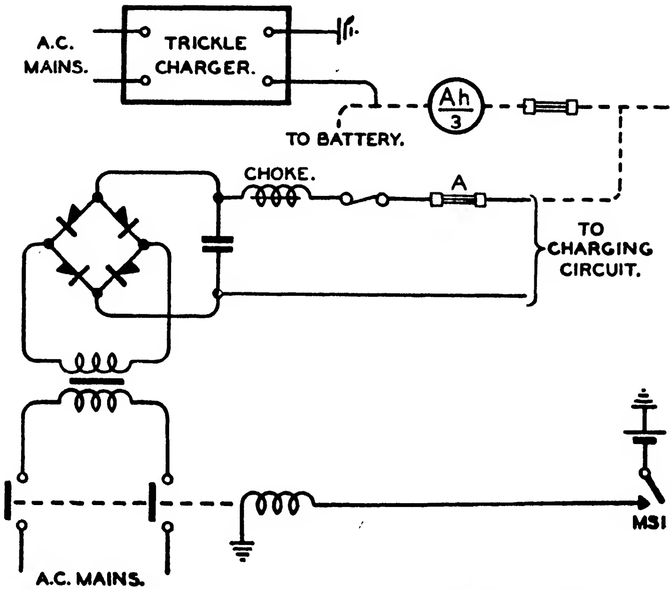


FIG. 164. PARALLEL BATTERY FLOAT SYSTEM CONNECTIONS FOR A.C. MAINS

Only one rectifier shown.

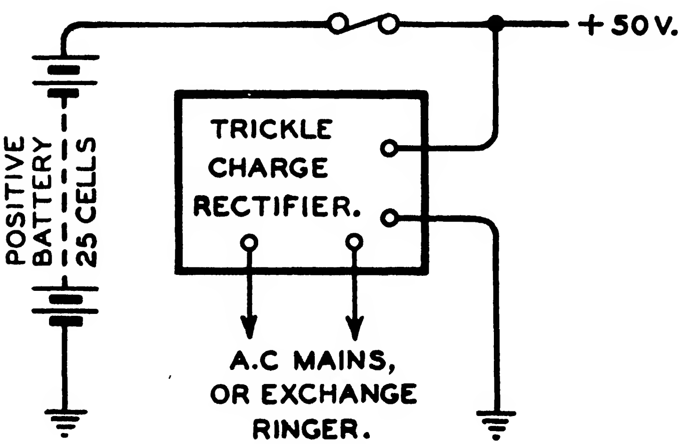


FIG. 165. POSITIVE BATTERY SUPPLY CIRCUIT

Meter Batteries. The 50-volt negative-earth meter battery is not provided in duplicate, but is connected permanently to a trickle-charge rectifier in all cases. Where the supply mains are a.c., these are utilized to feed the rectifier, but in d.c. cases the

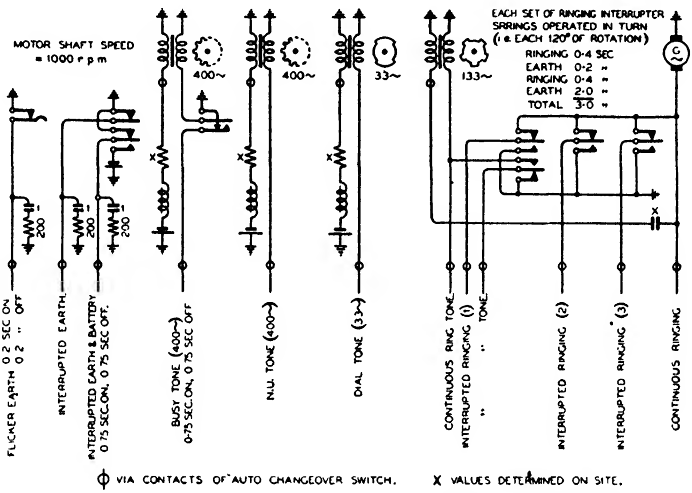


FIG. 166. CONNECTIONS OF INDUCTOR RINGER AND TONE SUPPLY MACHINE

a.c. output from the exchange ringer is adapted as a source of power (Fig. 165).

Ringing and Tone Supplies. The ringing current and tone supply for manual and automatic exchanges is obtained from special generators, supplying alternating ringing current at approximately 17 cycles per sec., and tones at 400, 133, and 33 cycles per sec. The machines are provided in duplicate, the No. 1 machine being driven from the public mains by a d.c. or a.c. motor and the No. 2, or 'stand-by' machine, being arranged for connection to the exchange battery busbars, for use in the event of the mains supply failing. The internal connections of the ringer and tone generator are shown in Fig. 166. In the larger mains driven machines, the direct current for the field coil of the alternator is obtained from a commutator connected to the alternator rotor at the opposite end to the slip-rings. The machine is therefore self-exciting. The motor is either of the squirrel-cage induction or synchronous type on

a.c. mains. The smaller a.c. machines have a rectifier incorporated to energize the field magnets, whilst in battery driven machines the 50-volt exchange battery is used (Fig. 167). In all cases the 17-cycle ringing is picked-up at the slip-rings. The

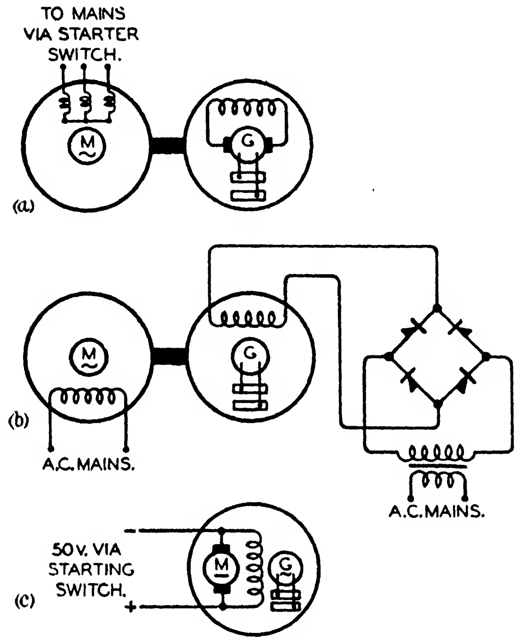


Fig. 167. Ringing Machines

(a) Large type ringer three-phase induction motor, self-excited generator.
(b) Small type ringer single-phase induction motor, mains excited generator.
(c) Battery driven ringer shunt d.c. motor common field excitation.

speed of rotation is approximately 1 000 r.p.m., the alternator being bi-polar.

Each tone is separately generated by induction, a toothed rotor of soft iron revolving in a magnetic field, the strength of which is adjustable. A second winding on the individual field magnets has induced in it an alternating e.m.f., the frequency of which is a product of the speed of rotation (in revolutions per second) and the number of teeth on the rotor. Thus no mechanical interrupters are necessary, and the tone generated is reasonably free from harmonics. To produce the 'busy' signal, the 400-cycle tone is taken through interrupter contacts driven from a low-speed shaft. The contacts make for 0·75 sec.

and break for the same period. Earth is connected during the 'no-tone' condition. In earlier systems, where 'balanced' tone supply is not used, the busy tone and flash were combined, and a busy hold circuit provided. These conditions are necessary

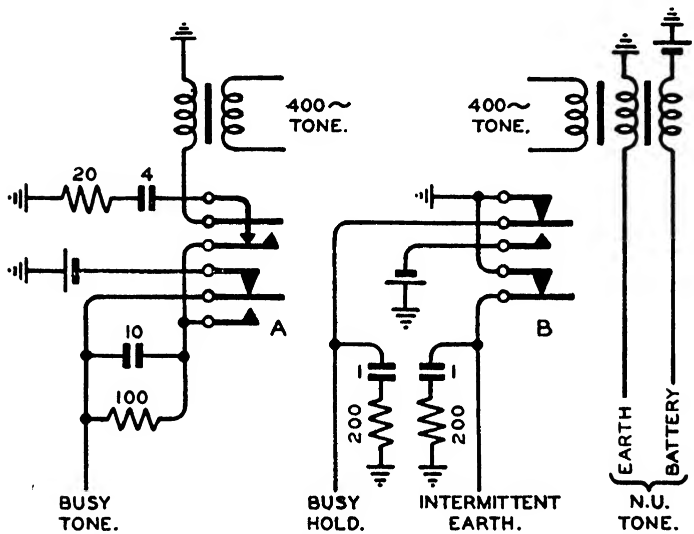


FIG. 168. ALTERNATIVE BUSY TONE, FLASH, AND N.U. TONE CONNECTIONS WHEN 'BALANCED' TONE IS NOT EMPLOYED

Note. Springset *A* is operated for 0·75 sec. while *B* is normal.
" *B* " " " 0·75 " " *A* " "

for the correct functioning of the automatic switches described in later chapters, and the modifications necessary to secure them are shown in Fig. 168.

Automatic Ringing Changeover. Should the supply mains fail, the ringer connected thereto ceases to generate, and the 'ring fail' condition is set up.

Fig. 169 shows the connections of the changeover circuit. Relays *K*, *L*, *M*, *N* are connected across the respective ringing leads, and control the release of relay *X*. Since the interrupters for the three ringing distributions function in sequence, the failure of any one supply will cause the release of *X*. *X*1 operates *ST*, gives the alarm, and operates the changeover switch trip coil at *ST*2.

The changeover switch is normally held in the upper position by the latch of the trip magnet, and the various switch blades

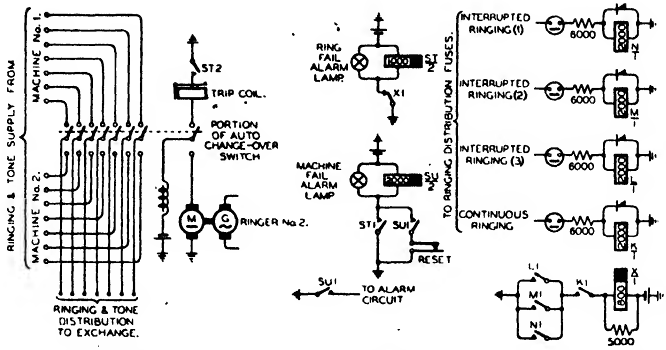


Fig. 169. Connections for Automatic Ringing Changeover

connect the exchange ringing and tone distribution leads to the No. 1 generator. When the switch is tripped the blades make contact instead with the output leads from No. 2 machine, which starts up immediately the switch has operated. If the output of No. 2 machine is satisfactory, all the ringing test relays reoperate, and relay X is again energized, releasing ST.

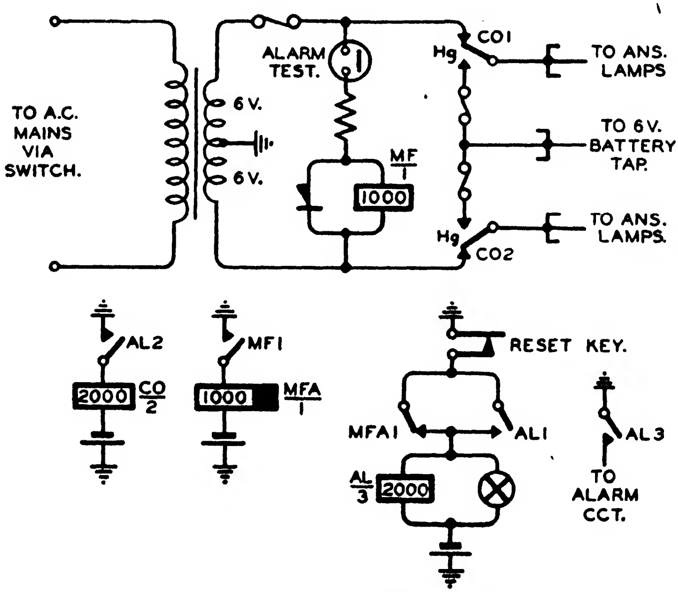


Fig. 170. 6-volt A.C. Supply for Answering Lamps
With emergency changeover to d.c. working.

SU, which operated at *ST*1, remains held over *SU*1 until restored by the operation of the reset key, and an urgent alarm is given.

The rectifiers shunting the ringing test relays ensure their satisfactory operation on ringing current, and the series resistances prevent a heavy load being applied permanently.

6-volt Supply for Switchboard Lamps. The answering multiple lamps, and the lamps used for the free-line-signal circuits in the outgoing multiples on manual switchboards, are usually worked from a 6-volt supply, since as each lamp requires only 40 mA. the total energy consumption is not nearly so high as when 50-volt lamps are used. Fig. 170 shows the arrangements adopted for the answering multiple, and the same scheme, with the absence of the emergency changeover, is used for the F.L.S. multiple. Relay *MF* is energized so long as the mains are live, but should they fail, *MF*1 releases *MFA* slowly, and *MFA*1 operates *AL*. *AL* locks via its own contact and the reset key, while *AL*2 operates *CO* to change over the supply to *DC*. *AL*3 completes the alarm circuit.

At each exchange employing 6-volt lamps, one of the main batteries is tapped at the third cell from the earth connection, and a lead is taken thence, via a fuse, to the emergency changeover circuit.

CHAPTER X

AUTOMATIC EXCHANGE CIRCUITS

The Automatic System. In the 'step-by step' system of automatic telephony, adopted by the British Post Office, subscribers in an exchange are divided into groups of 100, and *selectors* having 100 multiple outlets are employed to give access to the

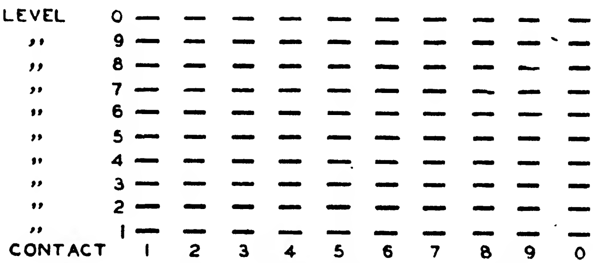


FIG. 171. GROUP OF 100 SUBSCRIBERS' LINES

lines in each group. The 100 lines are arranged on ten *levels* of ten contacts each, and the switches are stepped on a decimal basis, the last two digits of a subscriber's number determining the level and contact to which the selector wipers should be stepped (Fig. 171).

Each group of 100 lines may have to deal with several simultaneous calls, and the number of *final selectors*, as they are termed, which have access to each 100-line multiple is determined from traffic considerations. Each selector has its own complete multiple, the selectors usually being arranged in shelves of ten, the bank multiples being commoned between adjacent switches (Fig. 172).

One or more shelves will be required for each group, but all the switch positions need not be occupied. In such cases, the multiple banks are provided at the outset, and selectors added later as traffic increases.

If the exchange has a total of, say, 700 subscribers, there will be seven 100-line groups, each with several final selectors. Access to the individual 100-line groups is obtained from a previous *rank* of switches, called *group* selectors. These

selectors, which again each have access to multiple banks of 100 lines capacity, arranged in ten levels of ten contacts, account for the first digit of the subscriber's number. For instance, if subscriber 456 is required, the group selector is stepped to level 4. From this level, the ten contacts are wired to the individual final selectors serving the group of subscribers whose numbers range from 400 to 499. If there are less than ten final

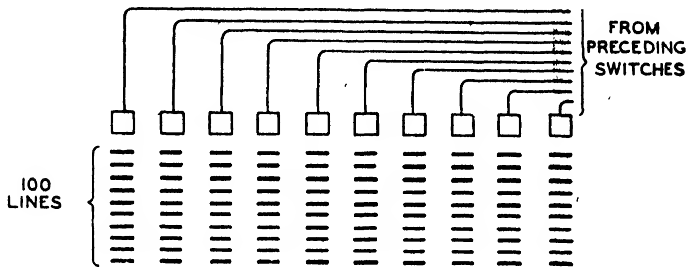


FIG. 172. FINAL SELECTORS WITH ACCESS TO ONE GROUP OF 100 LINES

selectors in the group, spare contacts are *busied*, whilst if there are more than ten, the outlets are *graded*.

In the case under review, as soon as the group selector wipers are stepped to level 4, they are rotated to search the level for a free outlet to a final selector in the required group. This rotation is automatic, and must be completed before the subscriber dials the last two digits, which are passed over the selected outlet to position the final selector wipers on contact 56 of the bank.

Each of the ten levels of the group selector multiple could be used to give access to one 100-line group, and on this basis 1 000 subscribers could be accommodated. However, it is customary to reserve levels 9 and 0 for manual board services, and one other level (often 8) is usually allotted to give access to one or more adjacent exchanges. In addition, level 1 is not used, as accidental misoperation of the subscriber's telephone, or intermittent fault conditions on the external line, are found to cause stepping of the selectors to this level. Only levels 2, 3, 4, 5, 6, and 7 remain, therefore, and this restricts the capacity of a three digit numbering scheme to 600 subscribers, numbered 200 to 799.

Such a scheme is shown diagrammatically in Fig. 173. Where

more than 600 subscribers require connection, a four-digit numbering scheme is adopted (Fig. 174).

An additional rank of group selectors is now required, and

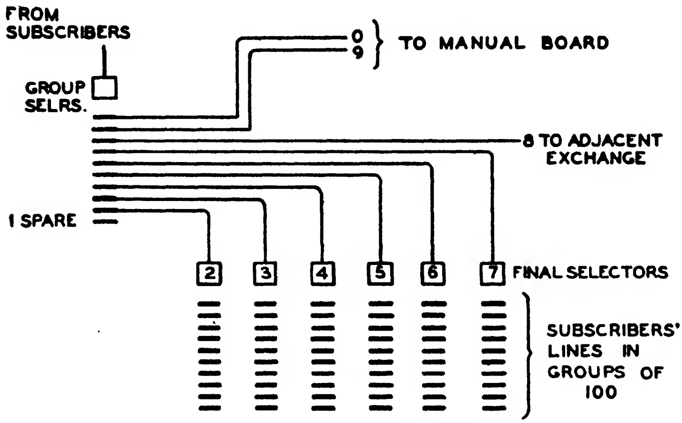


FIG. 173. THREE-DIGIT AUTOMATIC EXCHANGE

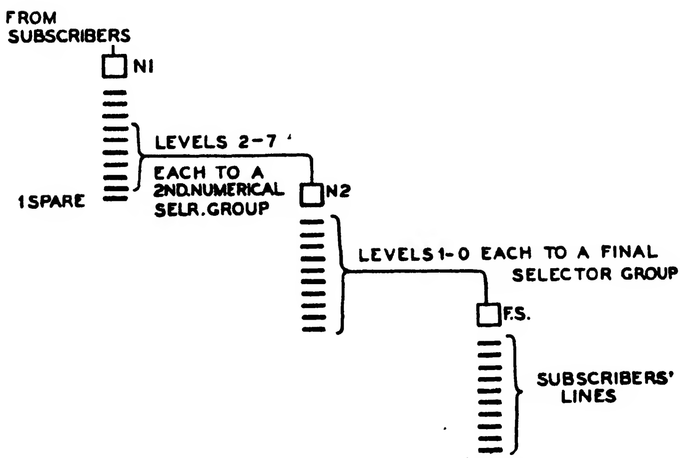


FIG. 174 FOUR-DIGIT AUTOMATIC EXCHANGE

these are termed *first numerical* group selectors, as they absorb the first, or thousands digit, and give access to the *second numerical* selectors, which are the equivalent of the group telectors in the three-digit scheme. The first numerical selectors sherefore determine to which thousands group the call is to be

connected, and the second numerical selectors determine the particular hundreds group.

Reserving levels 1, 8, 9, and 0 on the first numericals for the reasons stated earlier, capacity for 6 000 subscribers can be obtained from a four-digit scheme as described. For greater capacities than 6 000, special schemes are adopted.

Two-motion Selectors. The switches so far described have been two-motion selectors, i.e. they have a vertical motion to select the required level, and a horizontal motion to select either a free outlet to the next group, or the required subscriber's line, depending on whether the switch is a group or final selector. In the foregoing schemes each subscriber needs connection to a first numerical selector in order to obtain access to all the other subscribers. If switches were provided on this basis, the cost would be high, since each switch would require a complete 100-line multiple for access to second numerical selectors. Economy is obtained by taking advantage of the fact that only a small percentage of the subscribers will require to originate calls simultaneously. A common group of first numerical selectors is provided, and each subscriber is connected to a line switch, or *uniselector*, the bank contacts of which are connected to the first numerical selectors.

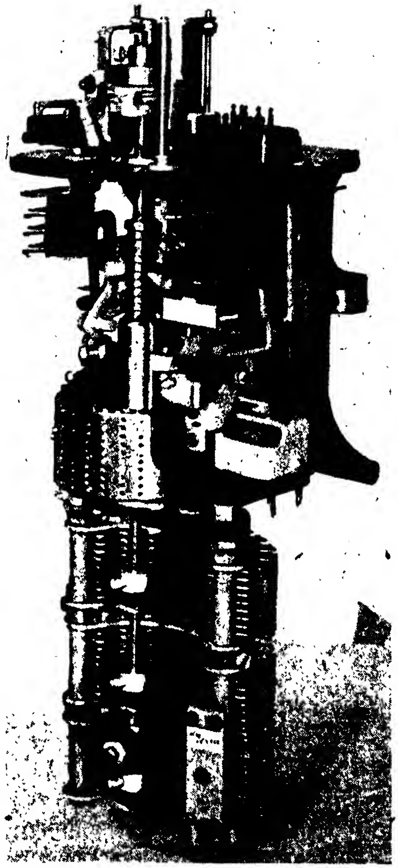


FIG. 175. TWO-MOTION SELECTOR MECHANISM
(*Siemens Bros. & Co. Ltd.*)

Single-motion Selectors. The uniselectors are single-motion selectors, consisting of a driving mechanism which rotates the switch wipers over a semicircular bank provided with twenty-five outlets. The circuit is arranged so that immediately the

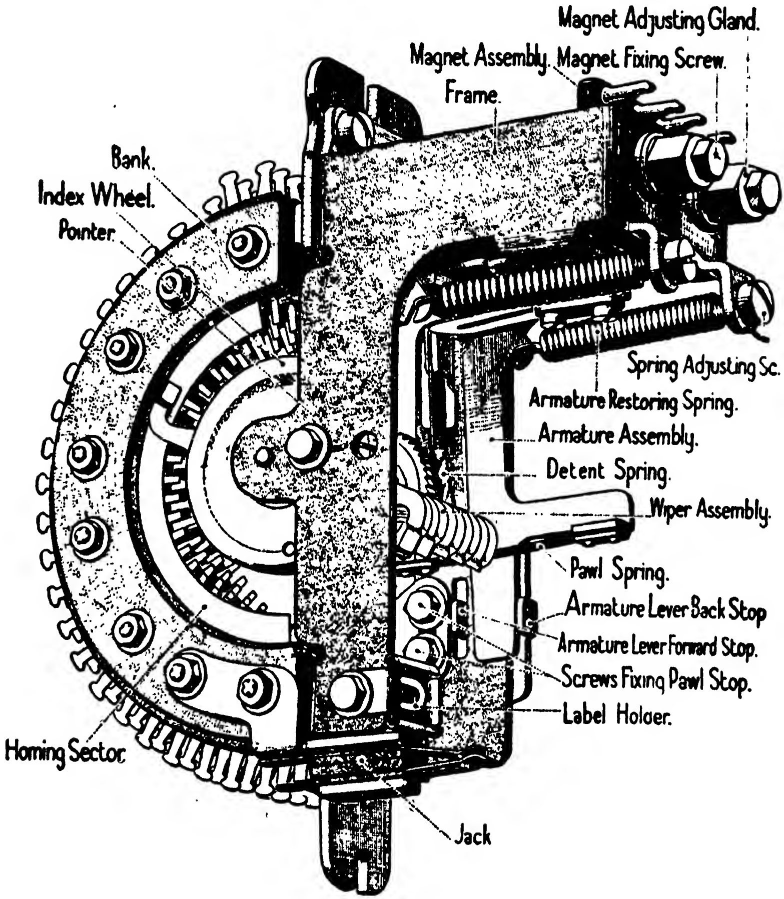


FIG. 176. UNISELECTOR

subscriber lifts his receiver, the line switch is energized, and its wipers are stepped over the outlets to first selectors, testing each in turn until a disengaged *trunk* (as the outlets are termed) is found. Dial tone is given to the subscriber from the first selector, and indicates that dialling may now commence. Fig. 176 shows the practical form of such a uniselector.

The time taken to test a maximum of twenty-five outlets is so short that, if a free trunk is available, the subscriber is connected before he has time to place the receiver to his ear, and in the later stages of switching, the automatic rotary

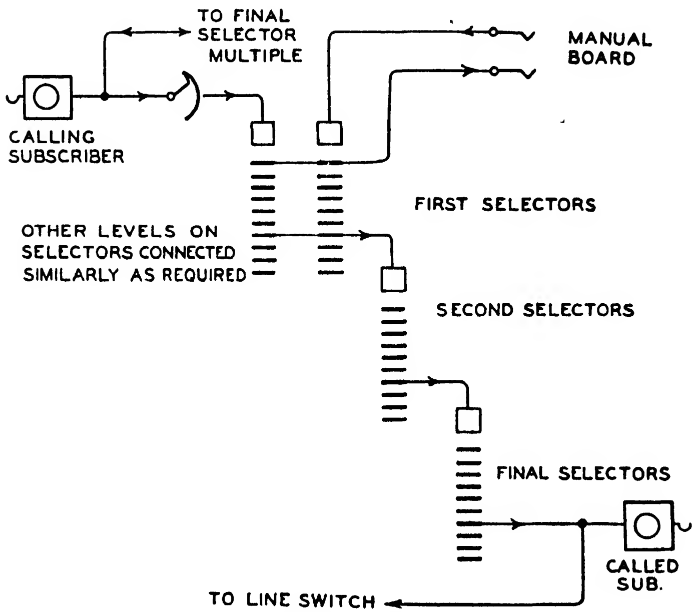


FIG. 177. FOUR-DIGIT SCHEME WITH UNISELECTORS AS LINE SWITCHES

search for a free trunk to a later rank of selectors takes place in the interval of time elapsing between the last 'impulse' of one digit and the first 'impulse' of the next.

Each subscriber's line equipment is cross-connected to the appropriate point in the final selector multiple bank, so that calls may be made both to and from his installation. Suitable precautions are taken to ensure that a subscriber's line on which an originating call is in progress tests 'engaged' at the final selector multiple until the first connection is cleared. A complete four-digit scheme, showing the subscribers' uniselectors, is given in Fig. 177.

Mechanical Features of Two-motion Selector. The two-motion selector in general use has three actions—vertical, rotary, and release.

The mechanism for the various operations is shown in Figs. 178 to 188.

For the vertical motion, the wiper shaft carries a ten-step cylindrical ratchet, and the vertical magnet armature carries a pawl on its extension, which engages with the ratchet teeth, and lifts the shaft one step for each operation of the vertical magnet. A double detent, held into contact with the teeth by

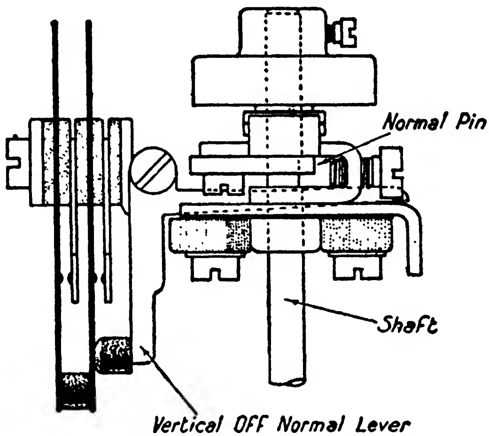


FIG. 178. 'OFF NORMAL' SPRING ASSEMBLY

spring tension, retains the shaft in the position to which it is stepped.

The rotary motion is effected by the operation of the rotary magnet, which also carries a pawl on the extension of its armature. When the armature is operated, the pawl engages with teeth cut on a hub keyed to the shaft, and rotates the shaft one tooth at a time. The same spring-loaded detent locks the shaft in position after each step has been taken, a fixed detent preventing any further vertical motion after the first rotary step has been taken.

Both vertical and rotary armatures are restored to normal by a spring after each operation. The tension of the springs is adjustable.

The release action is obtained by the energization of the release magnet, which merely disengages the double detent from the vertical and rotary ratchet teeth. A spiral cup spring on the shaft rotates it horizontally in the reverse direction to

that in which it had been stepped, until the fixed detent disengages—i.e. when the wipers are clear of the bank contacts. The shaft then drops vertically to the normal position with the wipers one step below the bottom level of the banks.

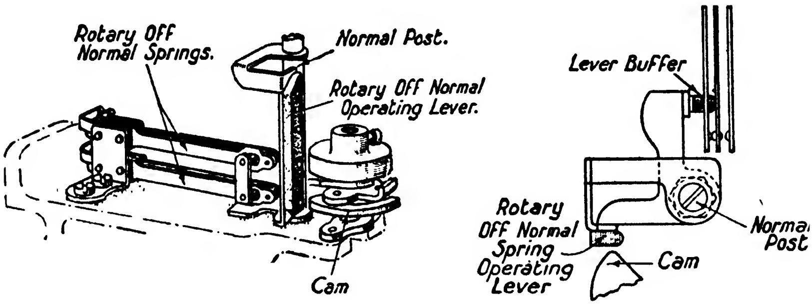


FIG. 179. ROTARY 'OFF NORMAL' SPRINGS

The following mechanically operated spring-sets form part of the switch mechanism, though their construction differs with various manufacturers.

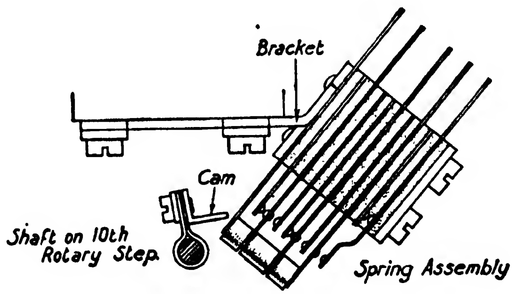


FIG. 180. CAM SPRINGS

Vertical 'Off-normal' or 'N' Springs. These operate as the vertical magnet armature steps the shaft up to level one, and they remain operated until the shaft returns to normal. Fig. 178 shows one method of operation.

Rotary 'Off-normal' or 'NR' Springs. These springs function on the first rotary step on any level and restore during release of the switch.

Cam, 11th Step, or 'S' Springs. The cam springs operate as the wipers are stepped to the 11th contact on any level. Bank

contacts are fitted on the 11th outlet, to prevent the wipers leaving the bank.

Release, or 'Z' Springs. The release magnet armature operates the 'Z' springs so long as the magnet coil is energized during release of the switch.

Vertical Marking Bank Auxiliary Wiper (A.W.). For special purposes (multi-metering, or discrimination for coin box or

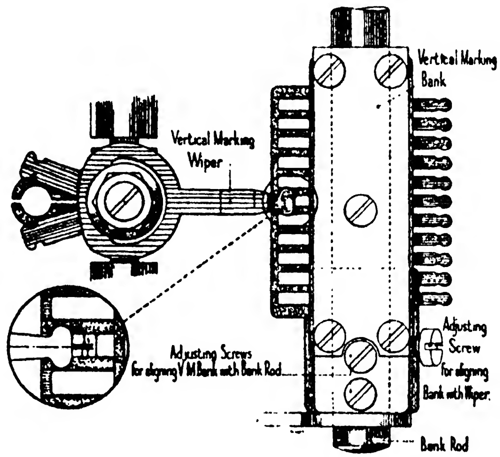


FIG. 181. AUXILIARY WIPER ON VERTICAL MARKING BANK

routing purposes) certain levels of a selector require different circuit conditions. A *vertical marking* bank is attached to the main bank assembly, and the auxiliary wiper connects with the relevant contact for any level to which the main wipers may be stepped. The wiring of the particular vertical marking bank contacts determines the circuit condition to be applied.

P.B.X. or 'Auxiliary Screw' Arc (A.S.A.). This fitment is used only on P.B.X. 2-10 line selectors. The auxiliary screw arc is fitted in front of the switch mechanism, and has a tapped hole corresponding to each bank outlet.. Screws may be inserted in these arcs as required by the allocation of P.B.X. subscribers, and the desired circuit conditions. Two wipers serve the bank, one being in step with the main wipers, and the other one contact behind (horizontally). The function of these wipers and screws will be clear from the circuit description.

Principle of Switch Operation. It will be noted that the wipers are moved either vertically or horizontally as the magnets operate, and the two-motion selector is therefore a 'forward drive' switch.

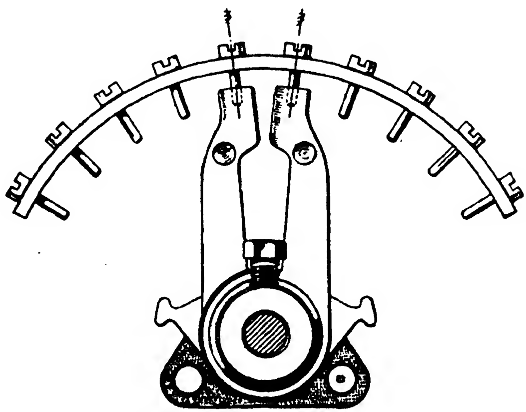


FIG. 182. A.S.A. WIPERS

Mechanical Features of the Uniselector. The standard uniselector, or single-motion selector used in telephone exchanges, is of the type shown in Fig. 176.

The wipers are held in position by a detent spring, which engages with the teeth of a ratchet wheel keyed to the wiper spindle. The ratchet wheel has fifty teeth, so that fifty operations of the driving magnet armature effect one complete revolution of the wipers. As the latter are double-ended, the twenty-five bank outlets are traversed twice in each complete revolution.

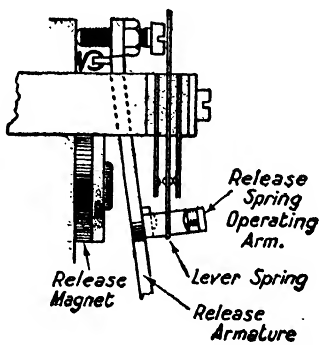


FIG. 183. RELEASE SPRINGS

The wipers are stepped on release of the driving magnet armature, and in this respect the uniselector differs from the two-motion selector in having reverse drive. As the magnet operates, an extension of the armature operates an interrupter spring-set, which breaks the magnet circuit and causes the armature to release. During operation, a spring pawl is moved

over one ratchet tooth, and during release, the pawl rotates the wheel by this amount, stepping the wipers to the next bank contact. This type of construction ensures, with correct adjustment, that the wipers must rotate one step for every

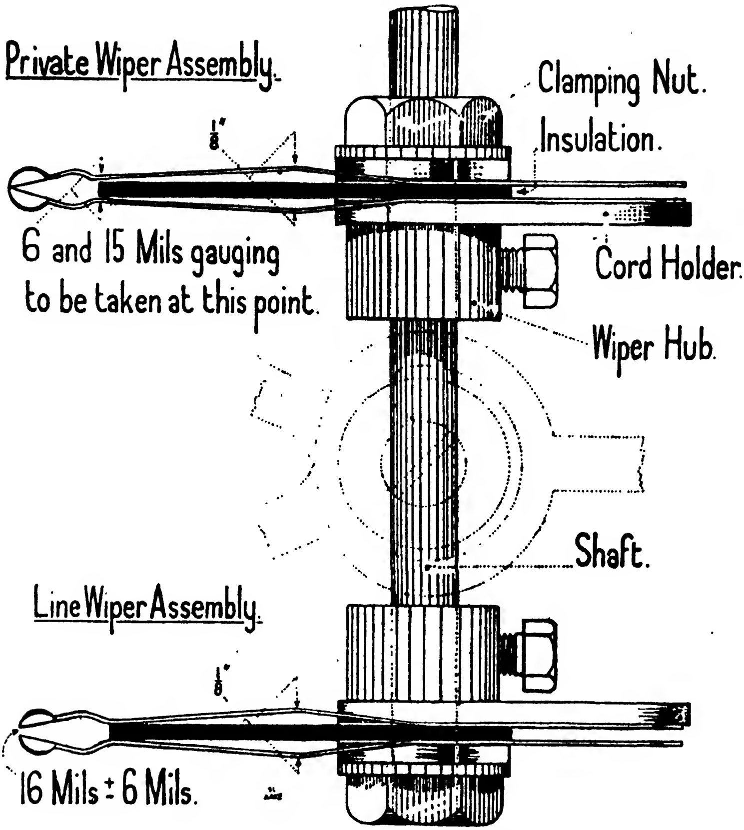


FIG. 184. LINE AND PRIVATE WIPERS

operation of the magnet. The self-interrupter arrangement can be used as the driven load is not great, and high speed of operation is essential. Three types of contact testing are employed.

(1) Ordinary wipers and contacts, of the 'non-bridging' type.

(2) 'Bridging' wipers, which connect during transit with the contact next ahead before leaving the one last occupied.

(3) 'Homing' arcs and wipers. Instead of separate contacts, solid arcs are used, except for the 'home' position. Sometimes the arc is split longitudinally, the two segments being normally insulated. During the passage of the wiper the two segments are bridged, this feature serving as an 'off-normal' indication in place of mechanical contacts.

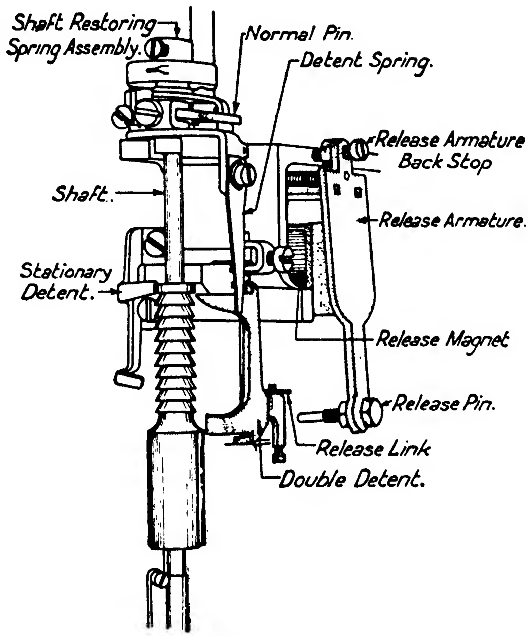


FIG. 185. NORMAL OR RELEASED POSITION OF SELECTOR

General Considerations. Automatic telephones are worked on the common battery principle, and a wet loop must therefore be the condition met with on the exchange equipment. Further, the dial which controls the stepping of the selectors must operate over the same pair of conductors as are used for conversation.

The functions of feeding speaking current and receiving dialled impulses are combined in the same relay on each automatic selector, and the characteristics of this relay will now be examined.

Impulsing Circuit. The subscriber's loop normally maintains the battery feeding relay continuously operated during the

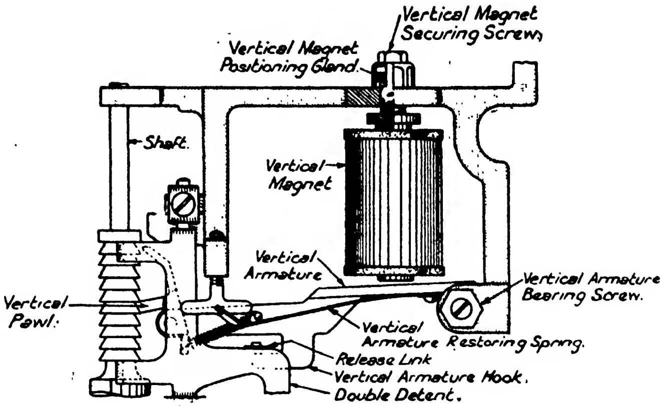


FIG. 186. VERTICAL STEPPING ACTION

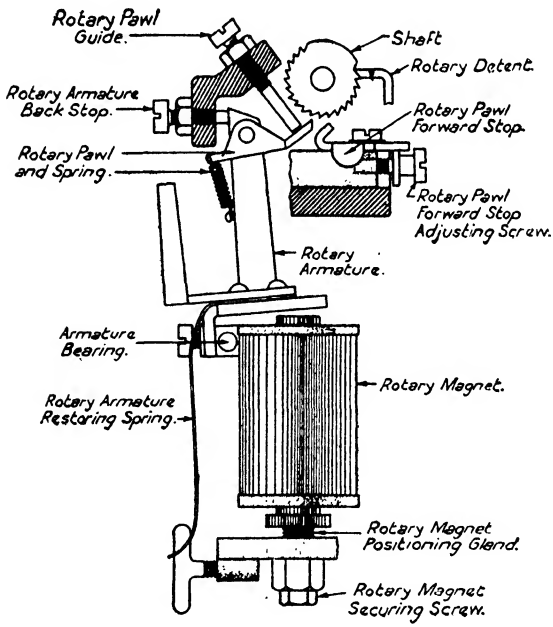


FIG. 187. ROTARY STEPPING ACTION

progress of a call, as in manual practice. The dial circuit is therefore arranged so that this relay is released momentarily, once for each impulse it is desired to transmit.

If the digit 4 is to be signalled, the subscriber's loop is interrupted four times in quick succession, and a corresponding number of times for the other digits. The impulsing relay responds to these interruptions, and steps the switch wipers accordingly, by means of electromagnets.

No impulses are transmitted until the dial has been first pulled round to the stop for the appropriate digit, and then released. A spring mechanism returns the dial to normal, and a toothed wheel actuates the impulse springs the correct number of times. The dial rotates under the influence of a mechanical speed governor, similar to that used in gramophone motors. Thus the rate of impulsing is maintained constant at about ten impulses per second, and the design of the toothed wheel is such that each impulse period consists of 67 per cent 'break' and 33 per cent

FIG. 188. 200-OUTLET SELECTOR
(*Siemens Bros. & Co. Ltd.*)

Fig. 189. Meter Rack

'make.' The impulsing springs are connected directly in series with the line, and the impulsing relay at the automatic exchange therefore has its windings in series with these springs (Fig. 190).

When not in use for impulsing, the contacts are, of course,

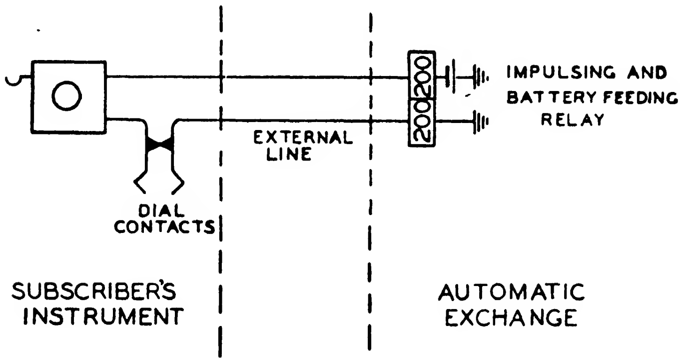


FIG. 190. IMPULSING CIRCUIT

closed, and the circulating current in the line flows through them.

Dial. The dial used in automatic installations is a fairly complicated piece of apparatus, and to ascertain the details of construction and operation it is best to see one taken apart and reassembled.

The main points in its construction are as follows.

The rotary finger-hole plate winds up the main spring on being pulled round in a clockwise direction, and also rotates the toothed wheel which controls the opening and closing of the impulse springs.

The latter are not actuated, however, whilst the wheel is rotated in a clockwise direction, owing to the shielding effect of a cam, termed the *slipping cam*, which is held by light friction to the toothed wheel. When the dial is released, the first few degrees of anticlockwise rotation bring the slipping cam up against a stop, and the teeth of the impulse wheel are thereafter exposed, actuating the impulse springs as many times as the rotation of the wheel permits. This is, of course, governed by the angle through which the finger-plate was originally turned. The last impulse (i.e. the impulse for the

FIG. 191. DIAL
Front View

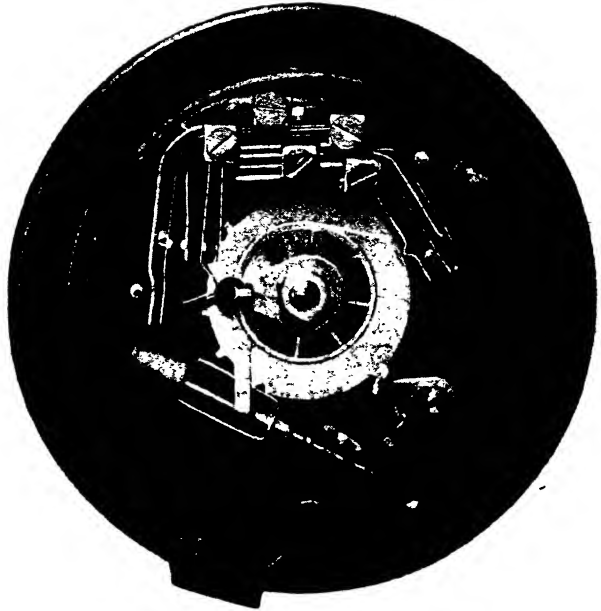


FIG. 192. DIAL
Rear View

(*Siemens Bros. & Co. Ltd.*)

digit 1) is given some time before the plate has returned to its normal position. This delay ensures that a certain time must elapse before the next train of impulses can be sent out, and is called the *lost motion* period. In conjunction with the time

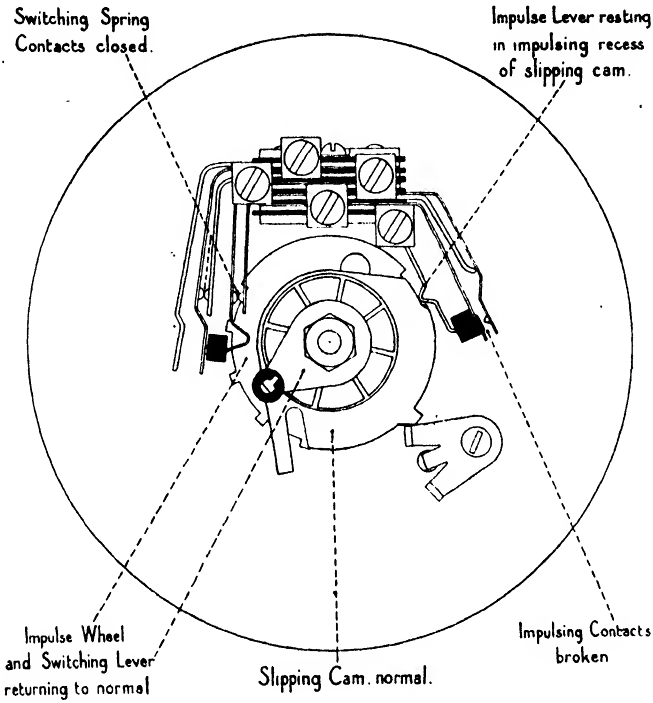


FIG. 193. DIAL
Mechanical features.
(*Siemens Bros. & Co. Ltd.*)

taken for the plate to be pulled round to the position determining the next digit, sufficient time is given for the automatic search feature on the selectors to take place. The least interval will occur during the dialling of successive digits '1,' '1,' and amounts to about 800 msec.

There are other springs on the dial besides those used for impulsing. They are termed the *off-normal* springs, owing to their being operated immediately the dial is moved off normal. They remain actuated during the whole time the dial is in motion, and are connected on the subscriber's telephone

circuit (*q.v.*) to prevent clicks and to improve the impulsing circuit.

The speed of rotation of the dial (which can be adjusted by bending the governor wings) must be maintained so as to give 10 i.p.s. of the contacts, and with a break-make ratio of 2 : 1, each impulse consists of 67 msec. break followed by 33 msec. make. The impulsing relay is designed to meet these conditions.

Impulse Distortion. The impulsing relay must offer a high impedance to speech currents, as it is placed across the line; and it is therefore highly inductive. The rise and fall of current in the relay during impulsing will therefore not be instantaneous, and moreover, owing to the considerable inductance of the relay coils, high induced voltages will appear on the break of the circuit. These voltages might reach values of several thousand volts if steps were not taken to reduce them, and damage to the insulation of the apparatus would result. The condenser (2 μF.) in the subscriber's instrument is utilized as a spark quench circuit, by being placed across the impulsing contacts while the dial is off-normal, and this results in a considerable lowering of the induced voltage on the 'break' of the contacts.

The resistance, leakance, and capacitance of the subscriber's line each have their effect on the impulsing circuit, and there are well-defined limits to the values of these properties of the line, which must be observed if impulsing is to be successful. A certain amount of distortion is, however, unavoidable, and the main effects can be summarized as follows.

(*a*) *Line Resistance.* Increases operating and decreases releasing lag of impulsing relay. This results in too long breaks and too short makes.

(*b*) *Line Leakance.* Tends to maintain impulsing relay in operated condition. Effect is the reverse of (*a*).

(*c*) *Capacitance.* Useful in absorbing induced voltages, but causes troublesome current surges, leading to contact bounce in extreme cases.

(*d*) *Inductance.* Retards the rise of current in relay coil, and so shortens make period. If present with capacitance, periodic circulating currents may be set up.

Fig. 194 shows the impulse wave forms under the various conditions and the design of the impulsing relay is a compromise

to obtain least distortion under average line conditions. The current in the subscriber's transmitter must not in any case fall below 50 mA. on account of speech considerations, and the maximum loop resistance that can be permitted for an automatic subscriber on a 50-volt system is 450 ohms. This allows for a small margin in battery volts, relay resistances, etc. (See further under "Ballast Resistance.")

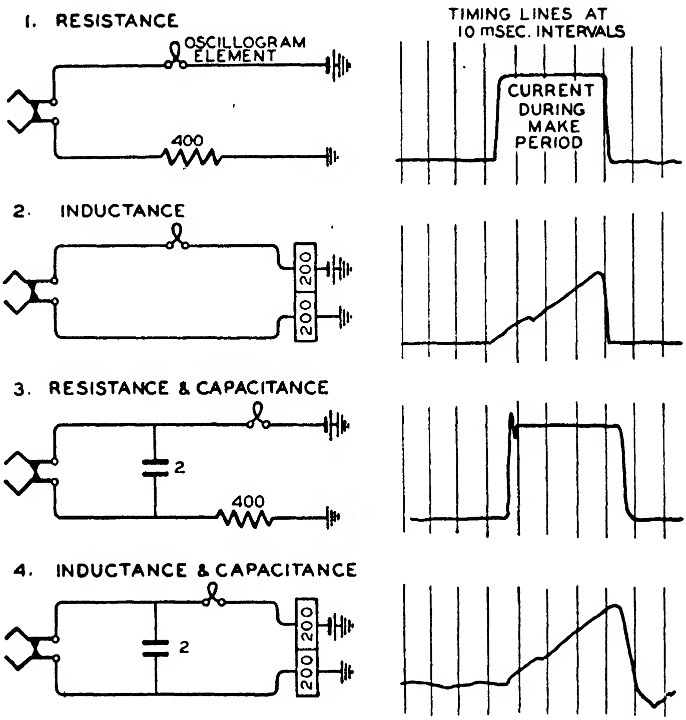


FIG. 194. IMPULSING WAVE FORMS UNDER TYPICAL CONDITIONS

Automatic Switching Circuits. The circuits used in Automatic telephony are necessarily complex, but in most cases consist of a combination of standard circuit elements; these can be analysed separately, and will then be easily recognized when the facilities afforded by a particular circuit are known. Impulsing from the subscriber's instrument has already been dealt with. The impulsing relay has two main functions—controlling the stepping magnets, and ensuring indirectly that the particular switch in which it is situated is not seized by another party.

In all circuits, the third wire, or 'Private,' is used for this purpose, and a slow-releasing relay is employed to maintain the earth potential which indicates the engaged condition. The earth may not be applied directly by the impulsing relay, as it would be momentarily removed during impulsing, so a relief relay, controlled by the impulsing relay, is added to the circuit. The relay is slow to release, so as to hold during the impulsing period, and also to provide an overlap when the guarding earth is to be fed back from a switch in the next rank (Fig. 195).

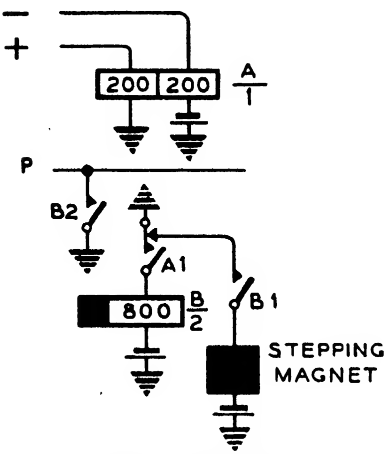


Fig. 195. Magnet Stepping Circuit

Testing Circuits. There are two main types of circuits used for the selection of free (or disengaged) outlets. They are—

(*a*) battery testing;
(*b*) earth testing.

The latter are used almost exclusively in the particular circuits described herein, but battery testing is being adopted as a general principle in circuits which will in time supersede those existing.

Battery Testing. The condition on the private conductor when the circuit is disengaged is connection to battery (negative 50-volt) via a resistance. When the circuit is engaged, a low resistance earth is substituted for the battery, and any testing switch encountering this earth is stepped on to the next contact. If the circuit is disengaged, the testing switch encounters the battery, which is used to arrest the stepping action and actuate the switching relay in the testing circuit. Conditions on the private wire are such that should two switches test in simultaneously, only one can be switched, whilst the other steps on. The great advantage of using this type of circuit lies in the fact that if neither earth nor battery is encountered on the private, as will be the case during the 'open' period whilst switches hitherto connected are releasing, the testing switch passes over the contact, thus avoiding the

troubles incidental to seizing a circuit during the release period. The operation of a typical battery testing circuit is given in Fig. 196.

In the through condition, the 25-ohm coil of K will be connected to the private of the chosen outlet, and will be held in series with the battery through 400-ohm from the switch

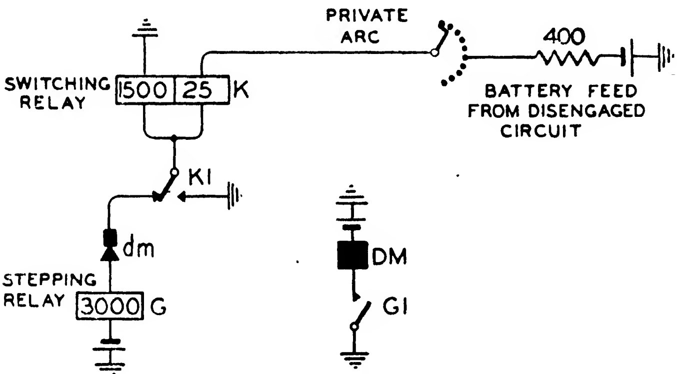


Fig. 196. Battery Testing Circuit

ahead. Consequently, when any similar circuit tests the same outlet, G operates in series with the 25-ohm winding of its corresponding K-relay, to the slight negative potential on the private. $G1$ operates DM, which releases G, and the cycle is repeated as long as battery is not encountered on the bank contacts. If an outlet is disconnected, G will operate in series with K (1 500-ohm coil) without operating the latter. When battery is picked up, G does not operate, but K is energized with current in both coils assisting. $K1$ applies low resistance earth to the private, to guard against the switching of other K-relays, and also disconnects G from the testing circuit.

Compared with earth testing circuits, the relay functions are much more critical, and the speed of testing generally slower, but immunity from double connections on simultaneous tests warrants the adoption of this type of circuit at critical stages in automatic switching.

Earth Testing (Fig. 197). The engaged condition on the private conductor is full earth potential, and a testing switch will step over all contacts thus marked, DM operating whilst K is short-circuited. If absence of earth is encountered, the

switching relay *K* will operate, the usual disengaged condition being that the private is disconnected. If two switches test simultaneously, there is a danger of both switching relays connecting to the same outlet and in this case, both calls are lost. During the release of switches the private must be momentarily disconnected, and in this 'unguarded' interval an earth testing switch is able to seize the circuit, causing undesirable circuit lock-ups and possible misrouting of the following call.

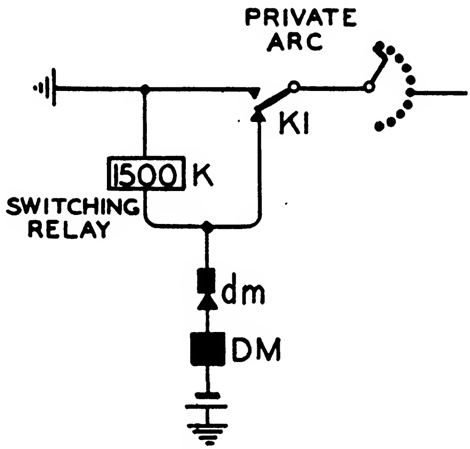


FIG. 197. EARTH TESTING CIRCUIT

The earth testing circuit is widely used, and its application to the various automatic circuits will be apparent.

Metering (Fig. 198). In modern metering circuits, the subscriber's meter is connected to the private conductor, and is operated at the moment when the called party lifts his receiver to answer a call.

The potential on the private conductor throughout the call is normally that of earth, i.e. the positive terminal of the exchange battery. At the instant the call is answered, this earth is momentarily substituted by a 50-volt battery (with its negative terminal earthed) and the potential of the private conductor is therefore raised above that of earth. Now all testing circuits pass earthed outlets because the 50-volt negative battery behind the testing relay causes a current to flow to the earthed private and operate the testing relay. Under metering conditions, a greater current will flow, as the batteries

are in series assisting, and the circuit therefore still tests engaged. The meter is connected to the private via a small rectifier, which allows current from the positive meter battery to flow, but stops current from the exchange negative battery. The meter is thereby actuated once on a normal call, the final selector circuit being designed to prevent more than one application of the meter battery. If 'multi-metering' is desired, special circuits are necessary, controlled from any selector

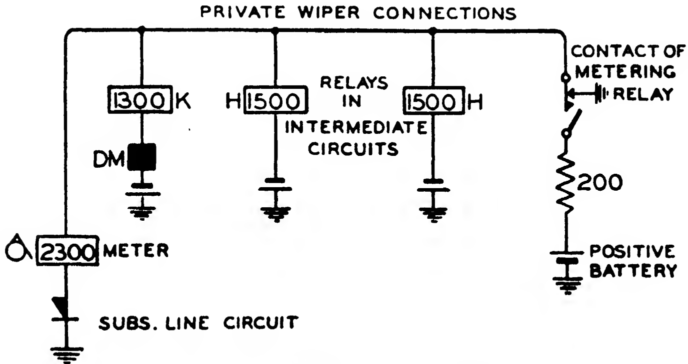


FIG. 198. METERING CONDITIONS

which absorbs a 'code' digit of the distant exchange to which connection is desired.

To permit the use of this facility, the subscribers' meters are 'non-locking,' i.e. they release after the metering pulse has been replaced by the normal earth on the private.

Busy Tone and Flash. Arrangements are made for the transmission of busy tone to the calling subscriber if the called subscriber's line is engaged, and also if the outlets to an intermediate rank of selectors are all occupied. The method of application will be clear from consideration of the individual diagrams, and the busy conditions applicable to the circuits about to be described are shown in Fig. 168. It will be noted that 'busy flash' is applied to the line during the period the tone is disconnected. The object of this is to 'flash' the supervisory relay on any circuit connected via a manual board, and thereby advise the controlling operator that the circuit is engaged without the necessity for continuous listening.

'Number Unobtainable' Conditions. All spare subscribers' lines and spare levels on selectors are connected to N.U.

(Number Unobtainable) tone. This is of similar pitch (400 cyc.) to the busy tone, but is uninterrupted. The battery applied on the negative line ensures the tripping of the ringing in the final selector circuit, but does not cause metering conditions to be applied.

Ringing and Ring-back Tone. The standard conditions for ringing subscribers on automatic exchanges are the application of alternating ringing current (17–25 cyc.) from an earthed generator to the negative line, and the connection of the 50-volt battery through a 'ringing return' resistance on the positive line. When the called subscriber lifts his receiver, the battery on the positive line, in conjunction with the earthed generator, ensures satisfactory tripping of the ringing irrespective of whether the call is answered during the 'ringing' or 'silent' period.

Ring-back tone is fed out to the calling party so long as the call remains unanswered. This is also the case when a manual board level has been dialled.

Supervisory Signals. On calls routed via manual positions, the state of the call (i.e. answered or unanswered) is indicated to the operator by means of the cord circuit supervisory lamp. The relay controlling this lamp is actuated by the conditions applied from the transmission bridge on the automatic selector or relay set. The standard supervisory signal on automatic junctions is reversal of the normal polarity of the lines to the calling party, i.e. battery is connected to the positive line and earth to the negative line, so long as the called party is on the line.

These reversals of polarity are detected by means of a shunt field relay (*q.v.*) or a relay circuit in which rectifiers are used to discriminate between the different directions of current flow.

Spark Quench Circuits. Some relays and all switch magnets have a high ratio of inductance to resistance, and when the large currents (from 0·25 to 1·0 ampere) which flow in their coils are interrupted at relay contacts, high induced voltages are produced, which will cause arcing and the consequent rapid destruction of the contacts. To prevent this occurring, spark quench circuits are used. With all magnet circuits, battery is permanently connected to one side of the coil, so that earth may be applied at the relay contacts, thereby avoiding the

danger of fusing relay springs by the accidental earthing of any which might have full battery potential connected. An earthed condenser is then joined in parallel with the coil, and will, in consequence, be permanently charged so long as the magnet is

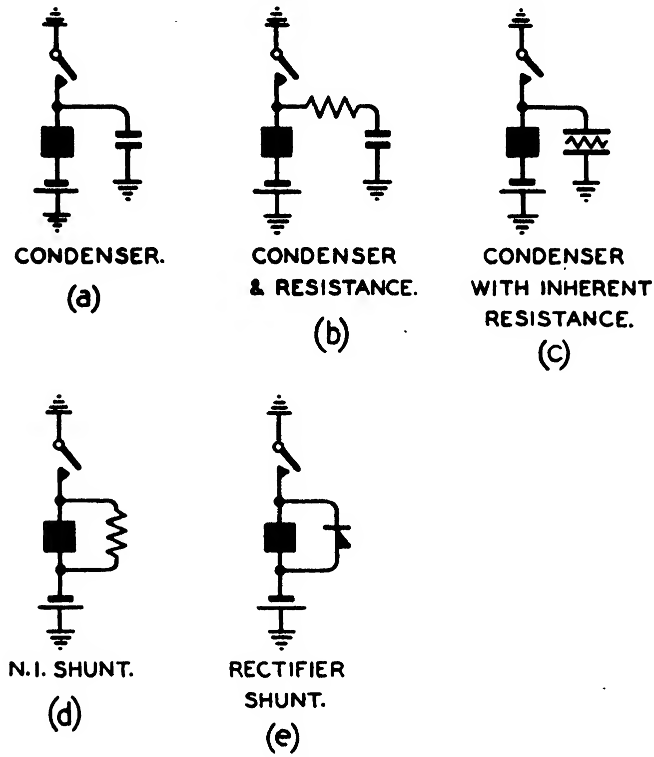


FIG. 199. SPARK QUENCH CIRCUITS

not energized. When earth is applied at the controlling relay contacts, the magnet is energized, and the condenser discharged to the same earth. On the subsequent break of the contacts, the condenser is recharged by the induced voltage appearing at the disconnected end of the coil and, with a suitable value of condenser, arcing at the relay contacts is eliminated.

The difficulty with this simple circuit (Fig. 199A) is that when the contacts make, the discharge current from the condenser flows across them, and in many cases will be sufficiently heavy to weld the contact points together. For instance, if the total ohmic resistance in the discharge circuit were one ohm, the

initial discharge current would have a value of 50 amperes, with a 50-volt exchange battery.

To overcome this defect, a resistance is inserted in series with the condenser, and limits the discharge current to $R/50$ amperes, where R is the series resistance. Different values of resistance and capacitance are used, depending on the current interrupted and the type of contact metal. The insertion of a series resistance, apart from diminishing the discharge current, unfortunately has an adverse effect on the absorption of the induced voltage, since it obviously takes longer to charge a condenser when a resistance is inserted in the circuit. A compromise is therefore effected, to obtain a balance between arcing at the break and welding on the make. Some magnet quenches are formed out of tinfoil grids placed between sheets of waxed paper, thereby combining resistance and capacitance in the same circuit. As platinum is used for all contacts interrupting magnet circuits, it is obviously economical to provide efficient spark quench circuits, so as to avoid renewal of the contacts at frequent intervals.

Another device often adopted is to shunt the magnet or relay coil with a non-inductive resistance, which provides a path through which the induced currents can circulate when the main circuit is broken.

This method is used for release magnet circuits, and has the advantage that the resistance may be wound on the same spool as the magnet coil, thereby economizing in space. The quenching is not so effective as when a condenser is used, and the resistance has a slight slugging effect on the coil. These defects are of minor importance when only occasional operation of the magnet is required. A rectifier may be used instead of a resistance, where a heavy slugging effect is desired.

Subscriber's Line Circuit (Fig. 200). The working of this circuit is as follows.

Operation on Outgoing Call. Subscriber removes receiver.

L operates to the line loop.

*L*1 and *L*2 complete operating circuit for *DM*.

DM operates, breaks its circuit at interrupter contacts, and in releasing, steps wipers to outlet 2.

If outlet 2 is engaged, *K* remains short circuited by *L*2 and earth on *P*-wiper.

DM reoperates, steps wipers to contact 3.

Cycle repeats until disengaged outlet is found, when *K* operates on removal of short-circuiting earth from *P*-wiper.

Disconnects *DM* at *K*1.

Switches subscriber's loop through to first selector on chosen outlet.

L remains operated, during its slow release lag (50 msec. approx.) to hold *K* at *L*2 until earth is returned on private from first selector.

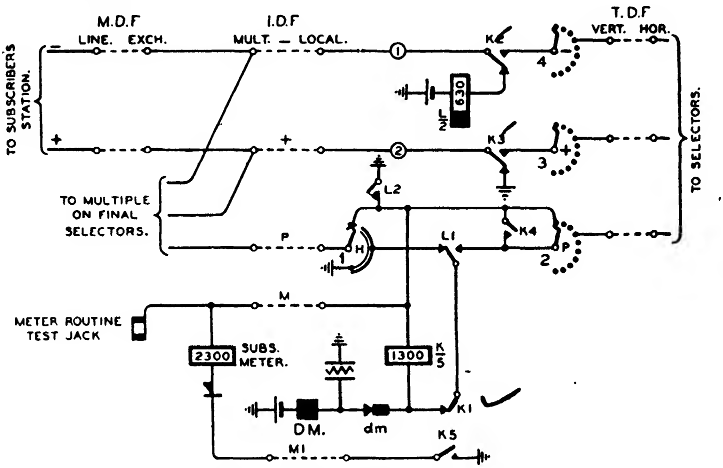


FIG. 200. SUBSCRIBER'S LINE CIRCUIT

K remains operated for the duration of the call, holding to earth or (positive battery) sent back from switches ahead. Meter operates in series with rectifier on receipt of pulse of positive battery on private.

All Outlets Busy. *DM* continues to operate, stepping wipers round bank until an outlet becomes free. No tone is given to subscriber.

Release. Subscriber restores receiver.

After release of slow relays in subsequent selector,

K restores on removal of earth from private.

DM operates via *K*1, *L*1, and homing arc.

Wipers are stepped back to home position, where

DM circuit is broken.

While circuit is in use, it is marked 'engaged' on final selector bank either by *L*2 or by wiper on homing arc.

Operation on Incoming Call. 1 000-ohm earth from final selector *H*-relay connected to private (multiple bank).

H and *K* operate in series. *H* applies full earth to private.

*K*2 and *K*3 remove calling equipment from line, giving final selector clear access to subscriber.

On release, *K* restores when final selector releases, and conditions revert to normal.

Special Features. (*a*) The private wiper is 'bridging,' i.e. during stepping it makes connection with the contact ahead before breaking from its contact last tested. The short circuit on *K* is thereby maintained, and sparking at bank contacts prevented.

(*b*) Contact *L*1 makes before *L*2, to prevent premature operation of *K*.

(*c*) Contact *K*1 breaks before *K*4 makes, to avoid false stepping of *DM* when outlet is free.

(*d*) The line wipers are always disconnected at *K*2 and *K*3 during rotation of the switch, to prevent interference.

(*e*) Outlet 1 is not multipled between switches, and is used as a 'home' position. On incoming calls, *K*2 and *K*3 switch to disconnected bank contacts.

Group Selector (100-outlet) (Fig. 201). The functioning of the component follows the following sequence.

Operation.

Subscriber's loop extended from preceding switch.

A operates (feeding dial tone to subscriber if switch is a first selector).

*A*1 operates *B* and *C*.

*B*2 returns earth to private to hold preceding switches,

*B*3 and *C*2 prepare vertical magnet circuit.

Subscriber dials, *A* releases for duration of break period of each impulse.

*A*1 operates vertical magnet and wipers are stepped to required level.

During momentary releases of *A*, *B* holds on slug.

On first vertical step, all *N* springs operate.

*N*1 leaves *C* dependent on current in *V* magnet circuit, but *C* holds on slug during impulsing.

After cessation of dialling, *C* restores.

Rotary magnet operates via *C*1, *B*1, *N*3.

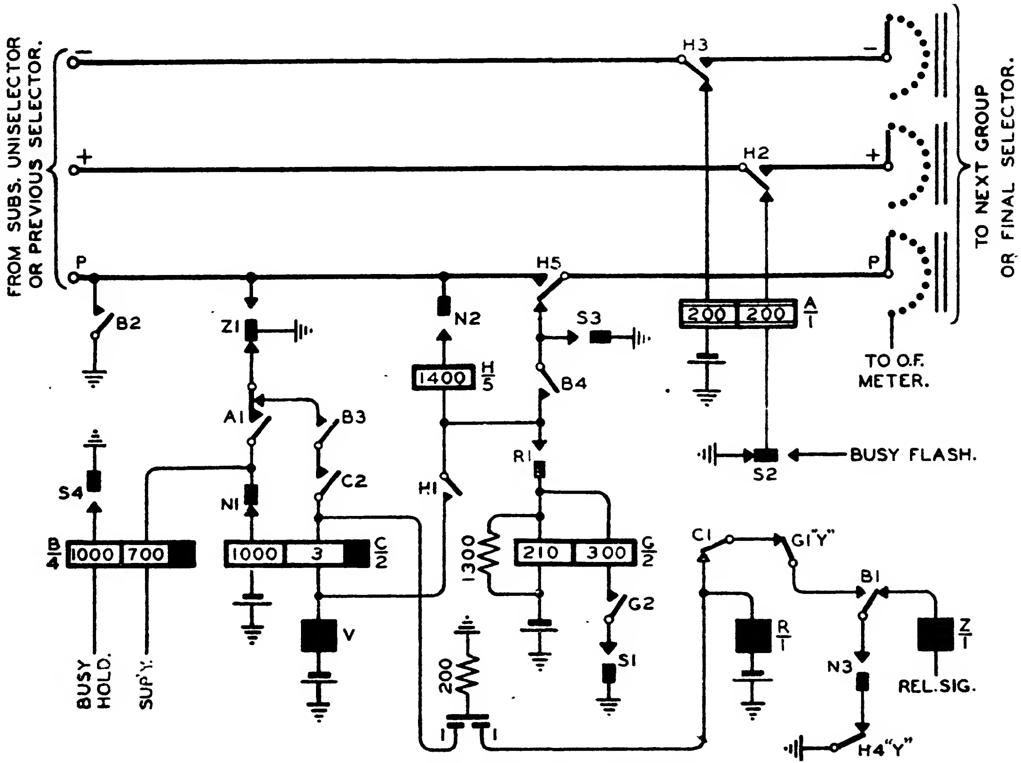


FIG. 201. GROUP SELECTOR. 100 OUTLET

Wipers step in and rest on contact 1 of level.

*R*1 operates, connecting *G* to private via *B*4.

If outlet engaged, *G* operates to earth on *P* and *H* is short-circuited.

*G*1 breaks *R* magnet circuit, *R* restores.

*R*1 breaks *G* circuit, *G* restores.

*G*1 remakes *R* circuit, *R* reoperates.

Cycle is repeated, wipers stepping round bank with *R* and *G* interacting until—

(*a*) A free outlet is found, when

H operates to earth at *B*2 via *N*2, due to removal of short-circuiting earth.

G does not operate in series, *H* locks via *H*1.

*H*4 disconnects *R*, which restores

*H*2 and 3 switch subscriber's loop through to next selector.

*H*5 completes through circuit for *P*-wiper.

A restores, and disconnects *B* at *A*1.

After approximately 400 msec. *B* restores.

H holds to earth put back from next selector.

(*b*) All outlets on level are engaged.

Wipers step to 11th contact (not multipled except for *P*-wire).

S springs operate.

*S*3 provides operating circuit for *G*, and energizes overflow meter to register congestion.

*S*1 and *G*2 give holding circuit for *G* on release of *R* magnet at *G*1.

*S*2 connects busy tone and flash to calling party.

*S*4 completes busy hold circuit for relay *B*, since *A* restores during busy flash period.

Release. (*a*) From normal call.

Earth is removed from private on release of subsequent selector.

H restores, completing release (*Z*) magnet circuit at *H*4, and reconnecting *A* relay to incoming lines at *H*2 and *H*3.

Z operates via *N*3 and *B*1.

*Z*1 replaces earth on private to prevent seizure of selector during release, also disconnecting earth from *B* relay circuit if selector should have been reseized before earth was reapplied.

Switch restores to normal, wipers rotating out of bank in reverse direction, then dropping.

$B4$ prevents false operation of H during release over P contacts with positive battery on them.

N springs restore as wipers pass level 1, releasing Z and returning conditions to normal.

(*b*) From 11th step of any level.

If subscriber replaces receiver during tone period, A restores.

$A1$ disconnects B, but B may still be operated due to slug when busy hold is reapplied (see Fig. 168), in which case normal release is initiated after cessation of busy hold pulse

If B restores before busy hold is reapplied, normal release conditions obtain.

If subscriber replaces receiver during flash period, A is already restored, but release, is delayed until after cessation of busy hold pulse on B.

Special Features. (*a*) $N2$ springs prevent H locking up whilst switch is busied for maintenance purposes.

(*b*) $G1$ and $H4$ break late to ensure full operation of R magnets on engaged and free outlets respectively.

(*a*) A supervisory lamp may be connected in parallel with relay B or C (1 000-ohm coil) when desired.

(*d*) Contact $A1$ is make-before-break to improve holding of B and operation of V during impulsing.

(*e*) H relay holds in series with vertical magnet to avoid provision of guarding resistance in series with $H1$.

(*f*) G holds with two windings in series to avoid overheating of coil on 11th step.

(*g*) 1 300-ohm non-inductive shunt on G coil prevents sparking at $R1$.

(*h*) P-wiper is bridging, to keep short circuit on H until free outlet is reached.

Group Selector (200-outlet) (Fig. 202). The operation of this switch is generally similar to that of the 100-outlet selector, up to the point where the C relay restores at the cessation of the impulse train. Then—

$C1$ completes the rotary magnet circuit, R operates, stepping wipers into the bank.

The 200-outlet bank has twenty private contacts per level, arranged in ten pairs of $P1$ and $P2$.

A pair of contacts is tested simultaneously by the top and bottom springs of the private wiper.

*If both P*1 *and P*2 *are Engaged.* *G* operates to the earth at *P*1, which also maintains a short circuit on *HA*.

The earth on *P*2 maintains a short circuit on *HB* and the 300-ohm winding of *G*.

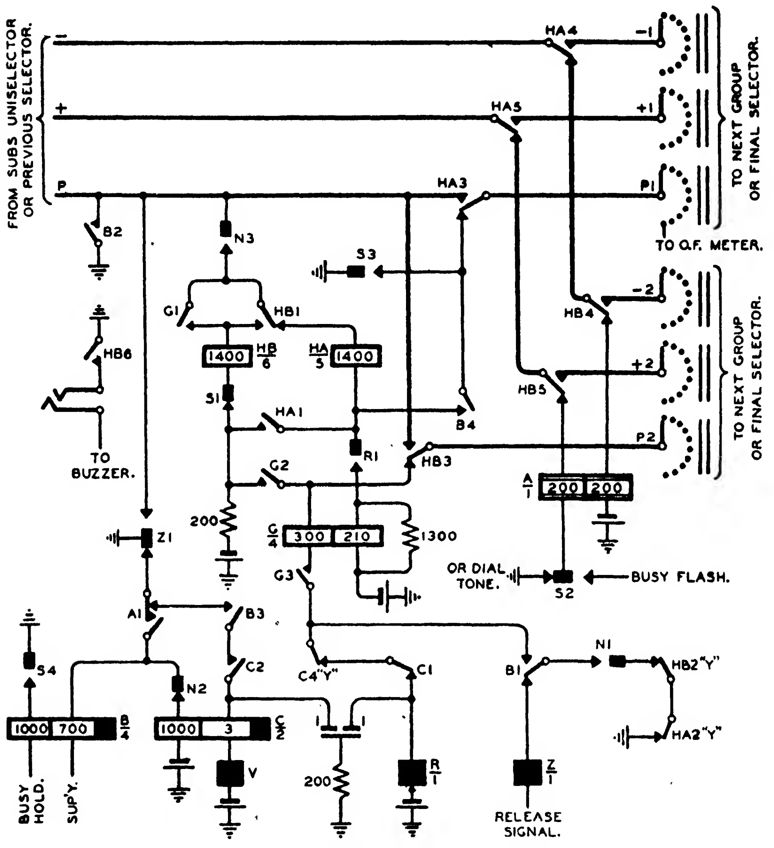


FIG. 202. GROUP SELECTOR, 200 OUTLET

So long as this condition persists, *G* interacts with *R*, and the wipers are stepped round the bank.

*If P*2 *only is Engaged.* On a particular contact *G* does not operate, and *HA* is energized in series, owing to the absence of the short-circuiting earth.

HB cannot operate on account of the earth on *P*2.

HA locks at *HA*1, and switches the subscriber through to the selector in the appropriate outlet.

*If P*1 *only is Engaged.* On a particular contact G operates as before, but does not restore immediately, since a holding current now flows in the second winding from battery via $G2$, $G3$, $B1$, $N1$, $HB2$, and $HA2$, to earth.

HB operates due to absence of short-circuiting earth at $P2$, locks via $HB1$, and disconnects HA and G.

The subscriber is now switched to the $P2$ outlet.

*If P*1 *and P*2 *are both Disengaged.* G does not operate, and consequently HB is disconnected. HA operates and definite preference is therefore given to the $P1$ outlet. This is desirable, since it allows the ten pairs of outlets to be considered for trunking purposes as a group of twenty consecutive trunks.

All Outlets Engaged. Under this condition, the wipers are stepped to the 11th contact of the level, and the cam springs (S) are operated. The overflow meter is energized from $S3$, and G holds on its 300-ohm winding. HA is short-circuited by $S3$ and $B2$, whilst HB is disconnected at $S1$.

The transmission of busy signal and release of the switch are the same as for the 100-outlet selector.

Special Features. (*a*) The switch test jack provides for operating a buzzer to determine whether the wipers are switched to $P2$ outlet or not.

(*b*) Three 200-contact banks are used.

Two banks contain 100 lines (— and + pairs) to final selectors, and the third contains the 100 pairs of $P1$ and $P2$ contacts.

(*c*) Dial tone can be supplied if the switch is used as a first selector.

Final Selector (100-line ordinary) (Fig. 203). The operations occur in the following sequence—

Ordinary Call. The subscriber's loop is thrown forward from the preceding switch.

A operates, $A1$ operates B, $B3$ operates C.

$B1$ earths the incoming private to guard the selector.

On receipt of the first and subsequent dialled impulses, A releases momentarily, energizing the vertical magnet via $A1$, $B5$, $C3$, and $E2$, and stepping the wipers to the desired level.

On the first vertical step, the N springs operate, disconnecting C from $B3$, and making it dependent on current pulses in the 3-ohm coil.

On completion of the 'tens' digit, *C* commences to release, and at *C*2 energizes *E*.

*E*5 reoperates *C*, *C*2 makes *E* dependent on earth via *C*2 and *E*1.

*E*2 changes over the impulsing circuit to the rotary magnet.

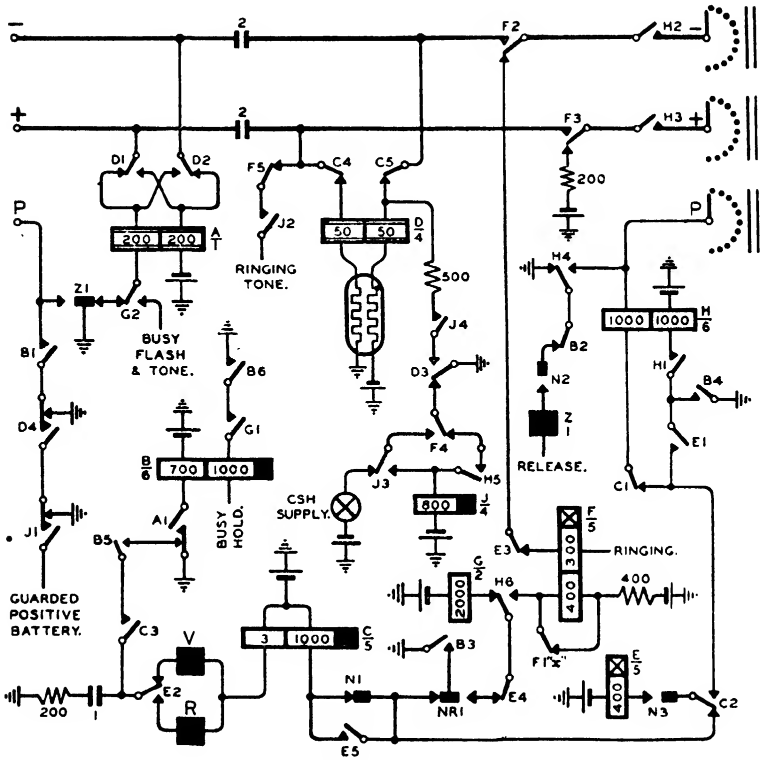


FIG. 203. FINAL SELECTOR, 100-LINE ORDINARY

The last, or 'units,' digit is now dialled and impulses *A* as before.

R is energized, and steps the wipers round the bank to the desired contact.

On the first rotary step, *NR* springs operate, leaving *C* dependent on the current pulses in its 3-ohm winding.

On completion of dialling, *C* restores, and at *C*1 connects *H* to the private of the dialled line.

If the line is Disengaged, H operates, and locks via $H1$. $H4$ applies a full earth to the private to energize K in the subscriber's circuit. $H2$ and $H3$ connect the — and + lines through to the ringing circuit which is completed at $E3$ on the release of E, which remained operated for the duration of its release lag after disconnection at $C2$. Ringing is sent out to the called subscriber, and J operates at $H5$.

Ringing tone is applied to the calling party's line via $J2$ and $F5$.

When the called subscriber answers, F operates due to current from the ringing return battery flowing through the instrument loop to earth via F coil and the earthed generator.

F locks at $F1$, and the wipers are switched through to the transmission bridge at $F2$ and $F3$.

J now holds via $J3$ and $F4$.

D operates to the called subscriber's loop, and at $D1$ and $D2$ reverses the polarity of the incoming lines for supervisory purposes or metering control over junctions. $D3$ disconnects J, which commences to restore, $D4$ replaces earth on the incoming private by positive battery via $J1$ until J releases, thus actuating the calling subscriber's meter.

D is held via $J4$ and $D3$ until J releases, preventing more than one operation of the meter should false release and reoperation of D occur.

$J2$ removes ringing tone, and J cannot now reoperate as F is locked up.

The call now proceeds until one party clears.

Calling Party Clears First. A releases, B releases after its releasing lag, H restores from $B4$, and the release magnet Z is energized via $B2$. The earth is removed from the private and from the various relay circuits by different B contacts, and the selector returns to normal. The called subscriber's loop is thrown on to his own calling equipment.

$Z1$ earths the private after a short interval to allow previous switches to restore, and breaks the operating circuit of A to prevent incorrect seizure of the switch during release.

Called Party Clears First. D only restores, and at $D3$ earths the C.S.H. ('called subscriber held') lamp, thus calling attention, by means of a deferred alarm, to the fact that the called party's line is being held engaged by a final selector.

When the calling party clears, the selector restores to normal as before.

Called Subscriber Engaged. On termination of dialling, C restores and connects H to the private. If the line tested is engaged, H encounters earth and does not operate. On restoration of E, G operates via $H6$ and $E4$, giving busy flash and tone to the calling subscriber at $G2$, and applying busy hold to B at $G1$.

Special Features. (*a*) $C4$ and $C5$ disconnect D from the transmission bridge during impulsing, thereby making the impulsing circuit similar to that of previous selectors.

(*b*) The ballast resistor in series with D ensures satisfactory transmission over long lines.

(*c*) E is slow to operate to allow the flux in the coil to reach a high value before C operates at $E5$, and thereby momentarily disconnects E during the transit time of $C2$.

(*d*) More than one meter pulse is guarded against by holding D via $J4$ and $D3$ until J has restored.

(*e*) The application of the ringing to line is delayed by $E3$ to permit K in the subscriber's line circuit to operate and disconnect the L relay and earth from the — and + lines, otherwise the ringing would trip prematurely.

Final Selector (200-line Ordinary) (Fig. 204). By giving each final selector access to two complete 100-line multiples, connection to any one of 200 subscribers may be obtained, with a consequent economy in switch provision due to the increased size of the group.

Three 200-point banks are fitted, wired as on the 200-outlet group selector, except that the outlets are subscribers' lines.

Six wipers are provided, and a switching relay WS determines to which set of wipers, and consequently to which group of 100 lines, the incoming call shall be routed. If access to the final selector is obtained from the lower level of a pair on a group selector, WS operates via earth, $H4$, $S2$, $N2$, 200-ohm resistance, + line to calling subscribers' instrument loop, — line, $WS2$, $B6$, to coil of WS connected to battery. WS locks via $WS1$ and the earthed private until the switch is finally released. The conditions are now normal, and the wipers are switched to the lower bank.

If the call has been routed from the upper level of the group

selector, *WS* is not operated on seizing the switch, and the circuit conditions are those of an ordinary 100-line final, with the wipers switched to the upper bank.

This circuit element can be applied to different types of final selector, often with one of the two 100-line groups arranged for 2–10 P.B.X. working.

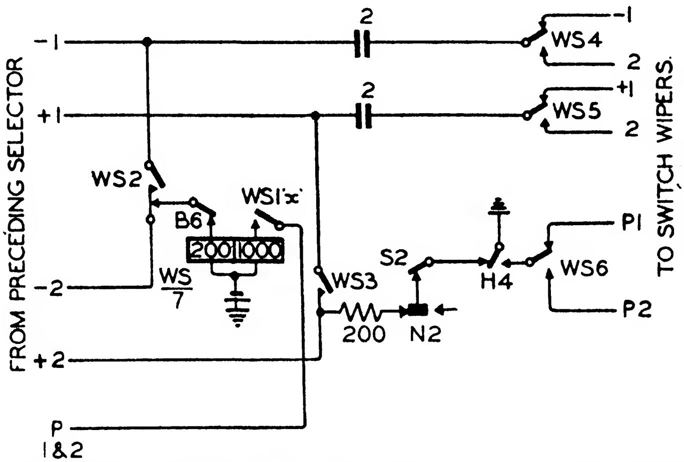


FIG. 204. CIRCUIT ELEMENT FOR 200-LINE FACILITY ON FINAL SELECTOR

Final Selector (100 or 200 lines) with 2-10 P.B.X. Facility on 100 Lines (Fig. 205). On all the lines of a 100-line ordinary final selector, and on the lower 100-line bank of a 200-line final selector, facilities can be provided for giving access to P.B.X. groups up to ten lines. The arrangement adopted ensures that—

(*a*) If the first line of a group is dialled, that line is selected if free. If engaged, the switch wipers are automatically stepped to the first free line in the group. If the last line is engaged, busy tone is given to the calling party.

(*b*) If any line other than the first is dialled, the switch behaves as an ordinary final selector. If the line dialled is engaged, busy tone is given to the calling party. This feature is useful when it is desired to extend individual P.B.X. lines at night.

A special arc is fitted on this selector, by means of which discrimination on P.B.X. lines is given. A solid semi-cylindrical metal sheet is drilled with holes tapped to take small screws in positions corresponding to the 100 lines on the switch bank.

The arc is fitted in front of the switch mechanism, and a pair of wipers makes contact with such screws as may be inserted in the lines corresponding to those on which the ordinary wipers are resting at any instant.

Screws are inserted into this auxiliary switch arc in the positions corresponding to all lines in each P.B.X. group,

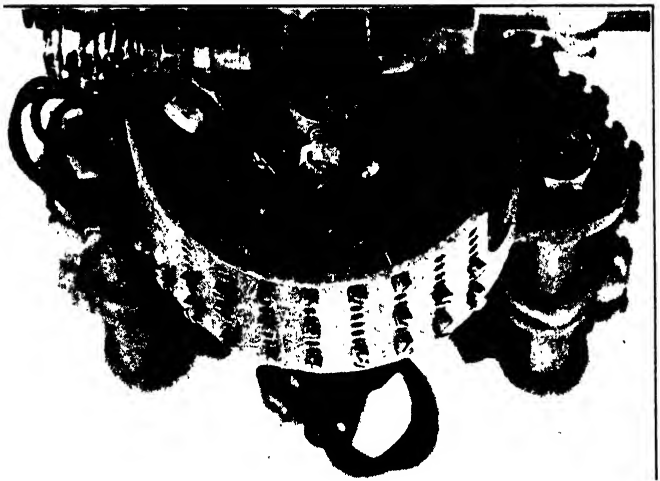


FIG. 205. P.B.X. ARC ON 2–10 FINAL SELECTOR
(*Siemens Bros. & Co. Ltd.*)

except the last in each group. The forward wiper of the pair serving the auxiliary arc makes contact with the screw appropriate to the line dialled, whilst the trailing wiper makes contact with the screw, if any, of the line one position earlier in the bank. The operations are as follows (Fig. 206)—

If the First Line of a P.B.X. Group is Dialled. If the line is free, *H* operates in the normal manner.

If engaged, *H* is not energized, and *HS* operates on release of *C* via *C*6 and the forward P.B.X. wiper to earth on the switch arc. *HS* is held over the same circuit during subsequent stepping of the wipers, until either *H* operates on a free line, or the last line of the group is reached, in which case the holding earth is removed from the P.B.X. arc. *HS*1 disconnects the trailing wiper and prevents the short-circuiting of *HS* during stepping.

The R magnet circuit is completed on the release of E at $E1$, via $HS4$, holding coil of HS, R magnet, 3-ohm coil of C, to battery; R and C reoperate, $R1$ reoperates E, and the wipers step to the next contact, R being disconnected at $E1$.

The cycle is now repeated with continuous interaction

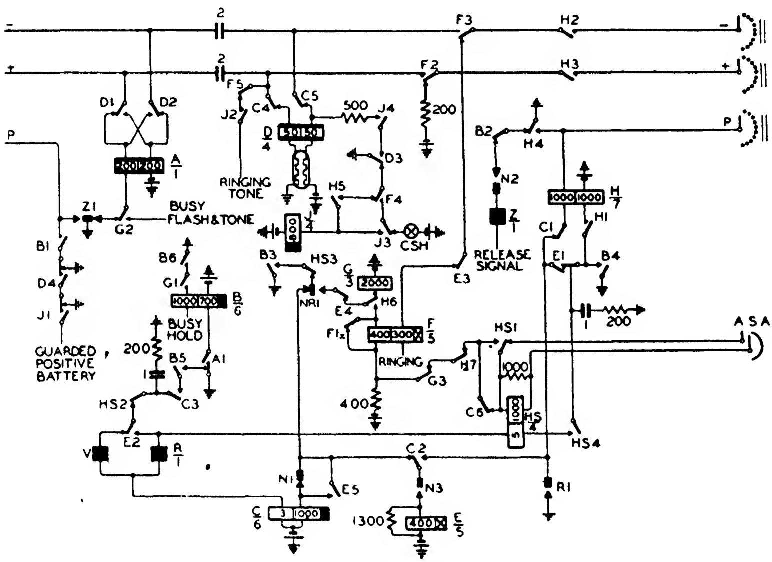


FIG. 206. P.B.X. 2–10 FINAL SELECTOR

between R, C, and E, until a free line is found or the last line is tested engaged. Under these conditions HS restores, and the circuit for G is completed on the final release of E. Busy signals are then given in the normal manner.

If a Line other than the First in a Group is Dialled. If the line is one of a P.B.X. group, the trailing wiper encounters earth on the P.B.X. arc and prevents the operation of HS.

If the line is an ordinary subscriber's, no screw will be inserted in the relevant hole, and HS will not operate.

In each case, the ordinary operation of H or G follows.

Special Features. (*a*) Relays E and HS are fitted with non-inductive shunts to prevent sparking when their circuits are interrupted during stepping.

(*b*) The hunting speed is determined by the releasing lags of relays C and E. The speed must not be less than 4 steps per sec.

11–20-line P.B.X. Final Selector. This switch caters for groups of lines up to a maximum of twenty lines per group, and has 200-outlet banks. Since each of the ten levels has twenty outlets, only 10-multiple numbers are needed to cover the 200 lines, and each subscriber has one level reserved for his own particular lines. The switch functions as an ordinary final

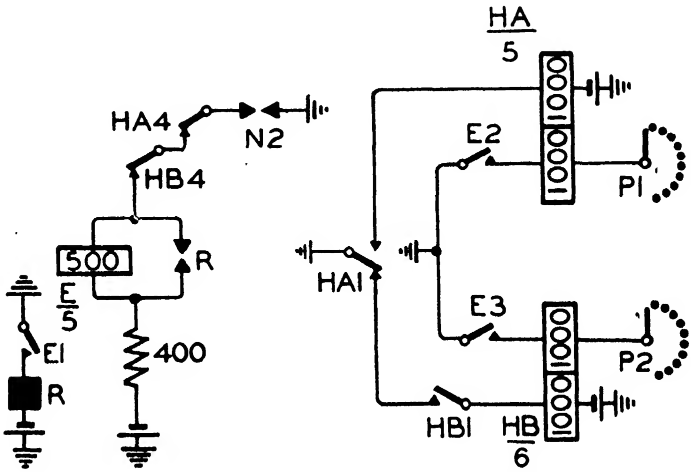


Fig. 207. P.B.X. 11–20 Final Selector
Testing circuit.

selector up to the completion of dialling of the penultimate digit, and from that point, as shown in Fig. 207, the search for a free line is automatic, as in the case of the 200-outlet group selector.

Operation (Fig. 208). Relays *A*, *B*, and *C* perform their normal functions after seizure of the switch and during receipt of the first digit. On release of *C*, during the intertrain pause, *DR* operates. *DR*2 operates *E*, which energizes the rotary magnet at *E*1, and the wipers are stepped into the bank on the desired level. The *R* springs close at the end of the stroke and short-circuit *E*, which releases slowly, de-energizing the release magnet. *E* reoperates, *R* reoperates, and the cycle repeats, the wipers stepping round the bank at a rate of from 2 to 4 steps per sec.

During each operated period of *E*, the earthed coils of *HA* and *HB* are connected to the private wipers P_1 and P_2, which

test the twenty outlets in pairs, one pair per rotary step. On engaged lines, the earths on P_1 and P_2 will prevent operation of either relay, but a battery encountered on either private will operate the corresponding relay and arrest the rotary motion.

If P_1 tests free, *HA* operates.

If P_2 tests free, *HB* operates.

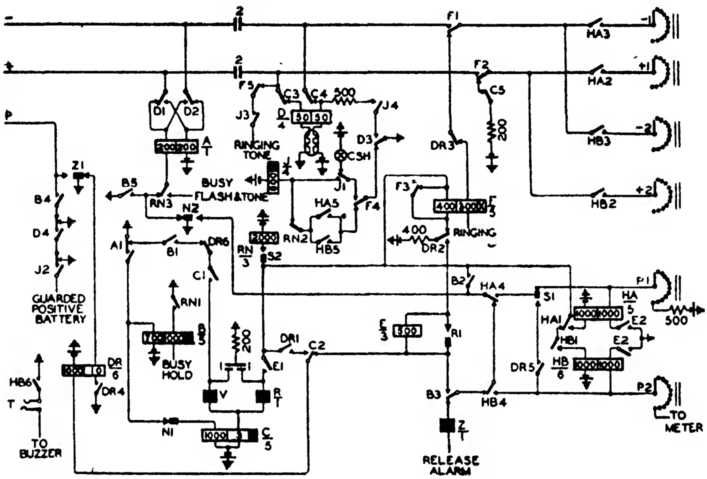


FIG. 208. P.B.X. 11-20 FINAL SELECTOR

If P_1 and P_2 test free, *HA* and *HB* operate, but *HA*1 breaks the holding circuit for *HB*, and preference is given to the P_1 choice. This feature permits the lines to be treated as a straight group of twenty outlets.

The operation of *HA* or *HB* prevents reoperation of *E*, and the calling party is switched to the appropriate line. *DR* is also released, and after its releasing lag (due to its short-circuited winding) ringing is sent out to the called party via *DR*3.

If all the lines are engaged, the cam springs (*S*) operate on the 11th rotary step, and *HA* operates to 500-ohm battery on P_1, *RN* is energized at *S*2, and applies busy flash and tone to the calling line, *RN*2 prevents the operation of *J*. The caller dials the last digit as the wipers are being stepped round the bank, but *DR*6 prevents any interference with the magnet circuits. The short-circuiting of the 10-ohm winding of *DR* via its own contact and the *Z* springs is to ensure quick operation

and slow release under normal conditions from $HA4$ or $HB4$. If the selector is released prematurely, however, Z operates and DR restores quickly, to guard against reseizure of the switch with DR operated.

Manual Board Circuit. Should the subscriber require a trunk or junction call, or desire to make an inquiry, access to the

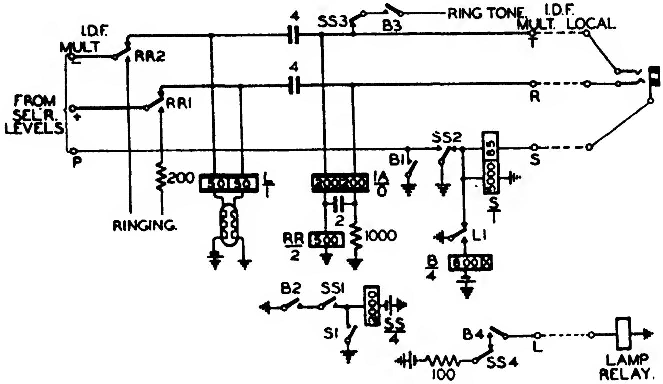


Fig. 209. Sleeve Control System
Manual board 'O' level circuit.

manual board is obtained from selector levels by dialling the digit or digits appropriate to the service required, e.g. 'O' for trunk calls, '91' for inquiry, etc.

Operation (Fig. 209). The subscriber's loop is thrown forward from the preceding selector, and L operates.

$L1$ operates B, $B1$ earths the private to hold previous switches and maintain the engaged condition. $B4$ energizes the lamp relay, which causes the switchboard lamps to glow.

$B3$ connects ringing tone to the calling line.

The operator answers with a sleeve control cord circuit (*q.v.*) and energizes S via $SS2$. $S1$ operates SS, $SS3$ disconnects the ringing tone, $SS4$ cuts off the lamp relay, and $SS2$ duplicates the $B1$ earth on the private, as well as removing the short circuit from the high resistance coil of S, thus dimming the cord circuit supervisory lamp. The call now proceeds in the normal manner.

Operator Clears First. The plug is withdrawn and S restores. SS is held via $SS1$ and $B2$ until the calling party clears, thus preventing the reappearance of the calling signal.

Subscriber Clears First (Manual Hold). L and then B restore, but the train of switches does not release, being held by $SS2$. This is the 'manual hold' feature, and prevents the subscriber making or taking another call until the operator has concluded the first. $L1$ short-circuits the 5 000-ohm coil of S, and causes the cord circuit supervisory lamp to glow.

Re-ringing Calling Subscriber. If the calling party, having cleared before the operator has finished, is desired to be recalled, the cord circuit ringing key is operated, sending out battery on the tip of the cord. RR is energized, and at $RR1$ and $RR2$ connects ringing to the line. The key is released to ascertain, by means of the supervisory lamp, when the subscriber again comes on the line.

Special Features. (*a*) The transmission bridge includes ballast resistance to give improved transmission on long distance calls.

(*b*) The 1 000-ohm resistor to earth on the ring side of the circuit is needed in conjunction with other relay sets which may be connected via the cord circuit.

(*c*) The 2 μF. condenser on the earthed side of the retard IA ensures equal impedance to earth of each line.

Ballast Feed Resistance. The standard transmitter feed conditions in automatic working consist of a relay with a 200-ohm winding in series with each line, and nickel-iron sleeve over the core to give the necessary high impedance for low transmission loss.

On long lines, the current in the subscriber's transmitter is reduced, and a loss occurs due to the falling off in transmitter output voltage. If the battery feed relay were of lower resistance, more than 100 mA. would flow on short lines, with a resultant liability of damaging the transmitter, and in any case the production of excessive 'side tone.'

The use of the ballast resistance feed, in conjunction with a relay winding, minimizes the bad effects of long lines. The ballast resistor itself consists of two fine tungsten wire elements in a glass tube containing hydrogen, and with low current values the resistance is approximately 50 ohms. As soon as the current rises, the wires heat up and their resistance increases rapidly, rising to nearly 300 ohms on a zero loop.

The increase in current as compared with a 200-ohm–200-ohm

feed is shown in Fig. 210, and the ballast resistor, together with one method of mounting, in Fig. 211.

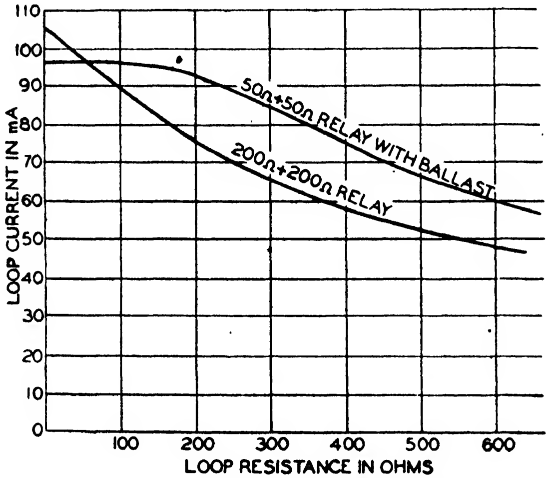


FIG. 210. CHARACTERISTICS OF BALLAST FEED

An improvement in the sending efficiency of 1·5 db. on subscribers' lines of 50 ohms resistance or over can be obtained

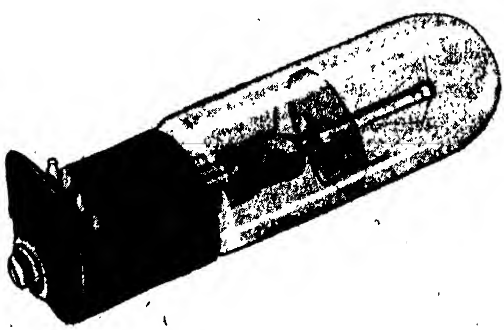


FIG. 211. BALLAST RESISTOR LAMP
(*Siemens Bros. & Co. Ltd.*)

by the use of ballast resistances, and these are therefore adopted for all transmission bridges except in the calling side of the final selector since, if the latter is utilized on a long distance call, a junction is connected to the calling side, whilst

in the case of a local call the slight gain in efficiency is not needed on account of the low overall loss in the connection.

Relay Set. Auto-Auto Junctions. Fig. 212 shows a typical relay set for use on selector levels outgoing to other automatic exchanges. The example shown caters only for calls

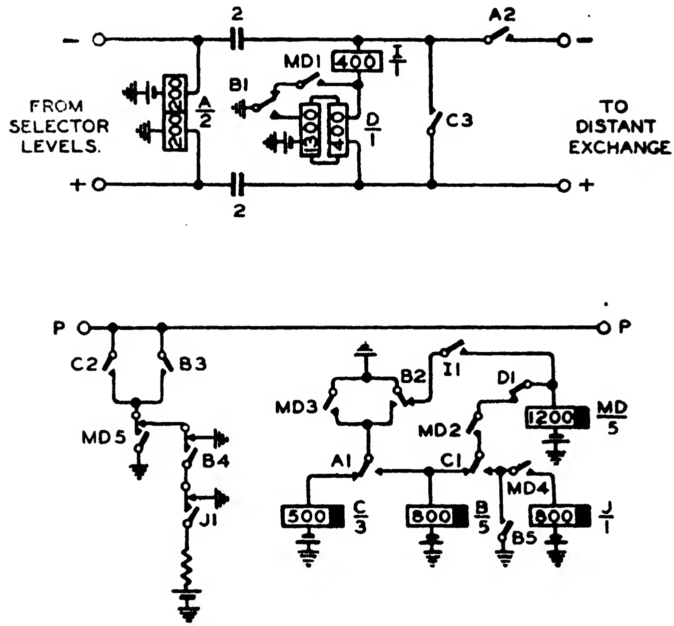


FIG. 212. AUTO-AUTO REPEATER
With manual hold and booster metering

from automatic subscribers, and therefore does not relay busy flash or supervisory signals, though these facilities may easily be obtained by the addition of more relays. The operation is as follows.

A is operated by the subscriber's loop switched forward by the preceding selector, and responds to the dialled impulses. *I* operates via *A*2 and the outgoing loop, and *I*1 energizes *MD*. *MD*3 completes the circuit for *B*, which earths the incoming private, and polarizes the *D* relay.

C operates on the first dialled impulse, and short-circuits the inductive relays *I* and *D*, leaving the loop clear for impulsing, during which *MD* holds via *C*1.

When the called party answers, *D* operates to the reversed

line polarity, and *MD* and *J* release in sequence. The metering pulse is applied to the private during the lag of *J*, which cannot again operate during the course of the call.

On release, *C* is energized again, and *B* and *C* release in sequence. The private is therefore guarded for the combined lags of *B* and *C*, and the relay set cannot be reseized until this period has elapsed. This feature ensures that any switches on the junction side have released before another call can be set up, otherwise misrouting would occur. If the call is to a distant manual board, the operator can hold the call even though the subscriber clears. Under these circumstances, *B* releases and *I* is held via *MD*1. *I*1 retains *MD*, which maintains the earth on the private.

CHAPTER XI

AUTOMATIC EQUIPMENT AND TRUNKING

Cabling of Automatic Apparatus. The selectors and relay sets used in a non-director exchange are mounted on racks with the apparatus shelf-jacks on one side, and the wiring and cabling on the other. Racks may be 10 ft. 6 in. or 8 ft. 6 in. high, and are arranged in bays, and served by travelling ladders.

All the subscribers' lines, and the majority of the selectors, are cabled to the I.D.F., where the distribution of the main circuits is carried out.

The multiple banks of the line finders, where used, are terminated on the I.D.F., but uniselector and selector multiples are cabled to Trunk Distribution Frames (T.D.F.) where the grading is effected.

The circuits to and from the manual board also terminate on the I.D.F., where relay sets appropriate to the circuits concerned may be associated. Outgoing junctions from selector levels to manual and automatic exchanges are brought through a Test Jack Frame (T.J.F.), which is cabled between the M.D.F. and the I.D.F.

The meters are housed on a separate rack, and are cabled to the multiple side of the I.D.F. Typical cabling and lay-out arrangements for a small non-director exchange are shown in Figs. 213 and 214.

Equipment for terminal amplifiers and for carrier working is also included in the apparatus room.

Equipment of Racks. The most economical provision of switches is determined from the traffic design, and it is usual for the equipment to be laid out on the racks in such a manner that extension is easily accomplished when the growth of traffic on the exchange warrants the provision of additional switching plant. The racks are generally 10 ft. 6 in. high, and are fitted with steel shelves of channel section. They are rendered easy of access by means of travelling ladders carried on overhead runways. Views of typical automatic plant are shown in Figs. 215–219.

Traffic Considerations. The number of subscribers' lines which can be connected to an automatic exchange is limited not only by the numbering scheme, but also by the traffic carrying capacity of the equipment. 6 000 subscribers will need 6 000 calling equipments, but 300 first selectors might suffice

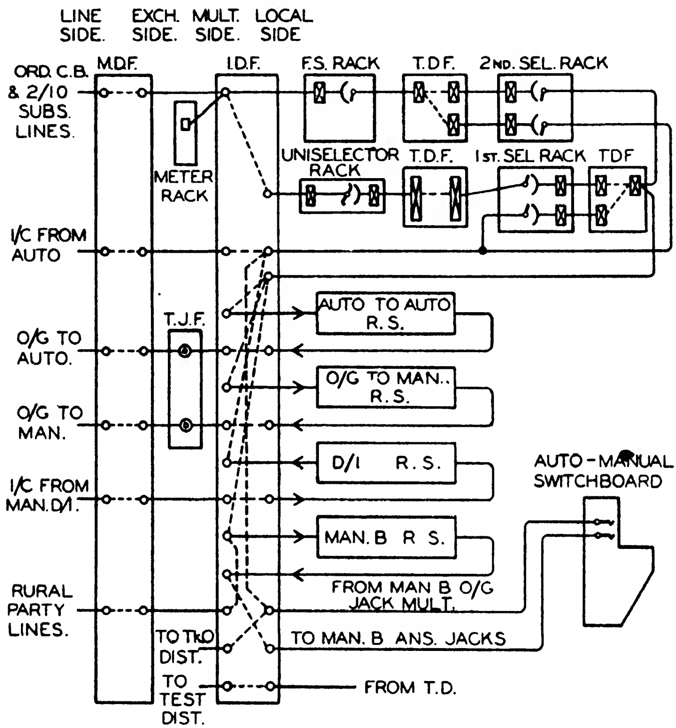


FIG. 213. CABLING SCHEMATIC FOR NON-DIRECTOR AUTOMATIC EXCHANGE

to carry the whole of the originated traffic if the lines were not very busy.

Each first selector level carries the whole of the traffic for the group of numbers commencing with the relevant digit, and the contacts in this level must serve a number of switches capable of carrying the maximum number of calls likely to be passed. Again, each second selector level must give access to a sufficient number of final selectors to carry the maximum number of simultaneous calls to the particular group of 100 lines.

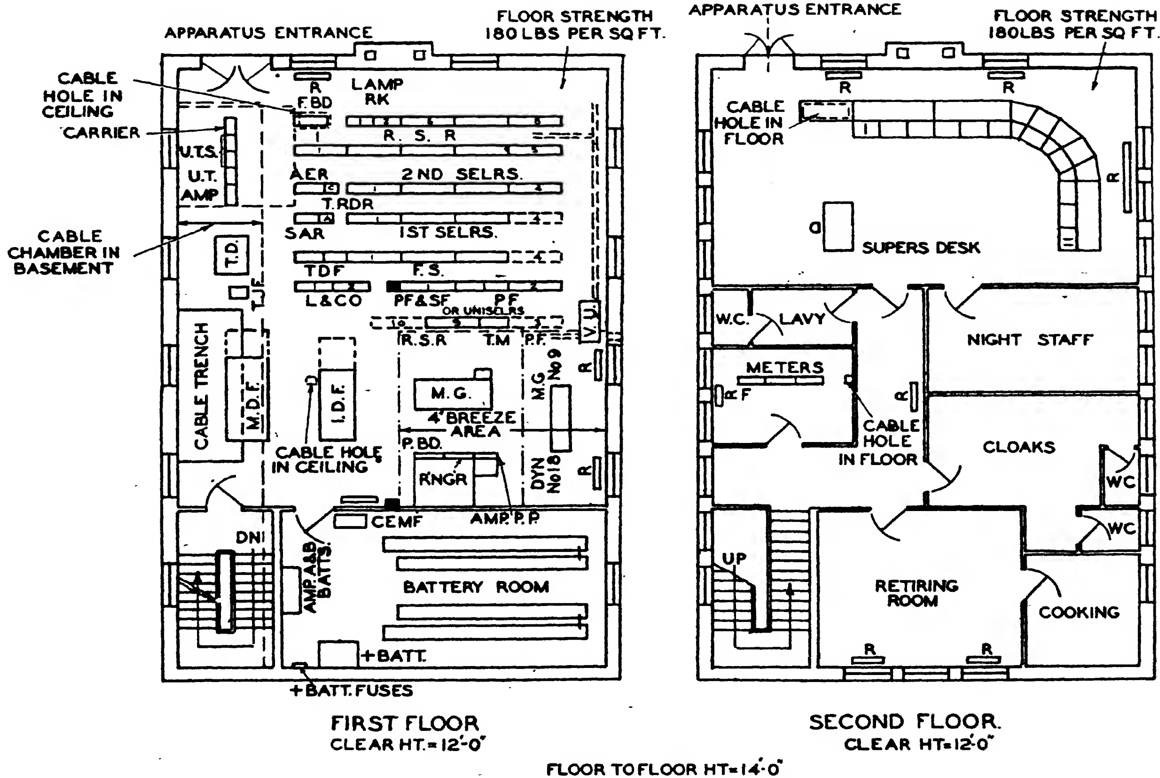


FIG. 214. LAY-OUT OF AUTOMATIC EXCHANGE

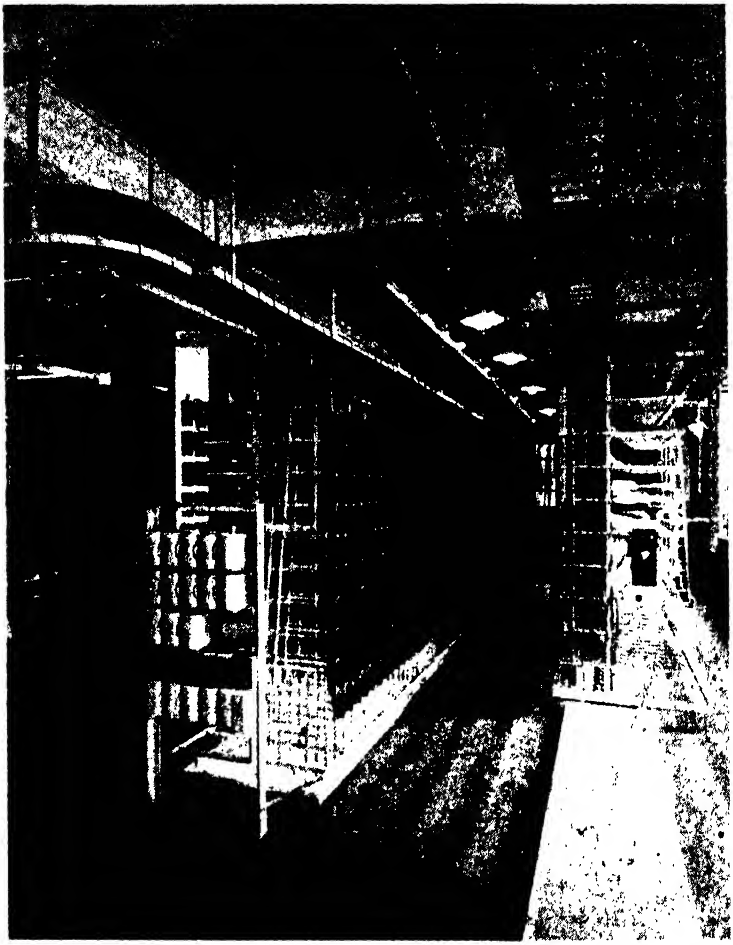


FIG. 215. INTERMEDIATE DISTRIBUTION FRAME
(*Siemens Bros. & Co. Ltd.*)

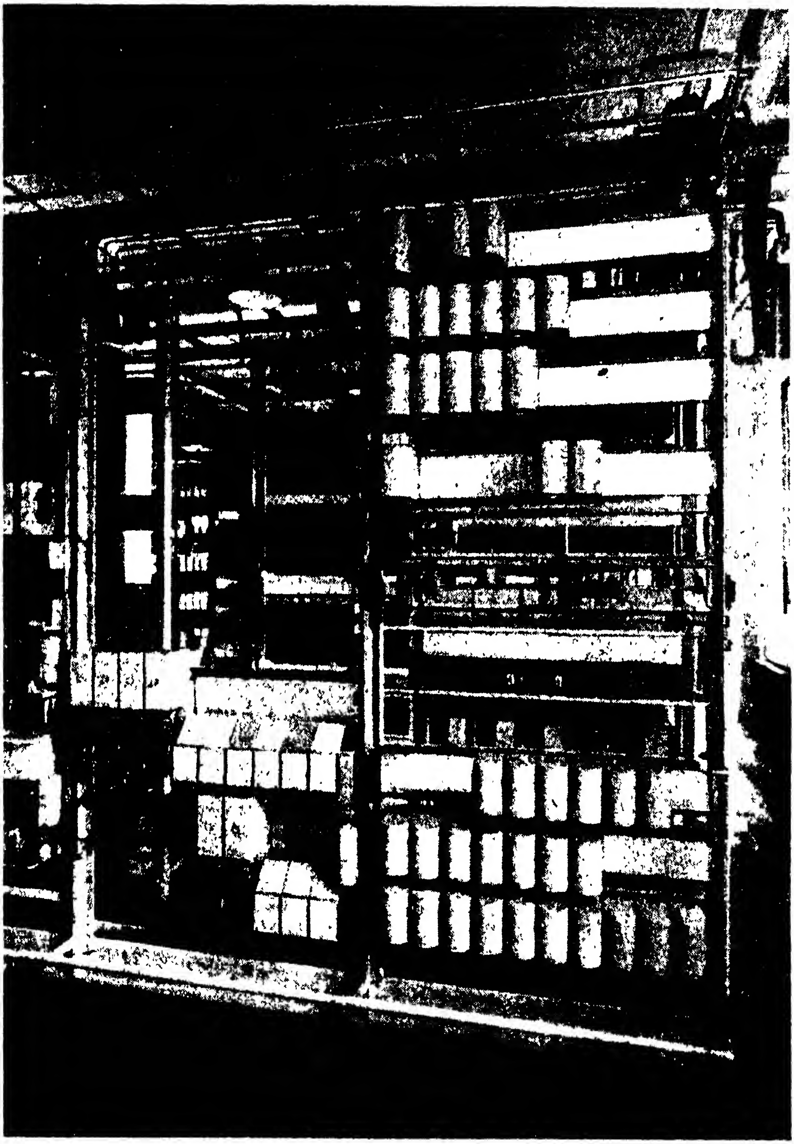


FIG. 216. RELAY SET RACK
(*Siemens Bros. & Co. Ltd.*)

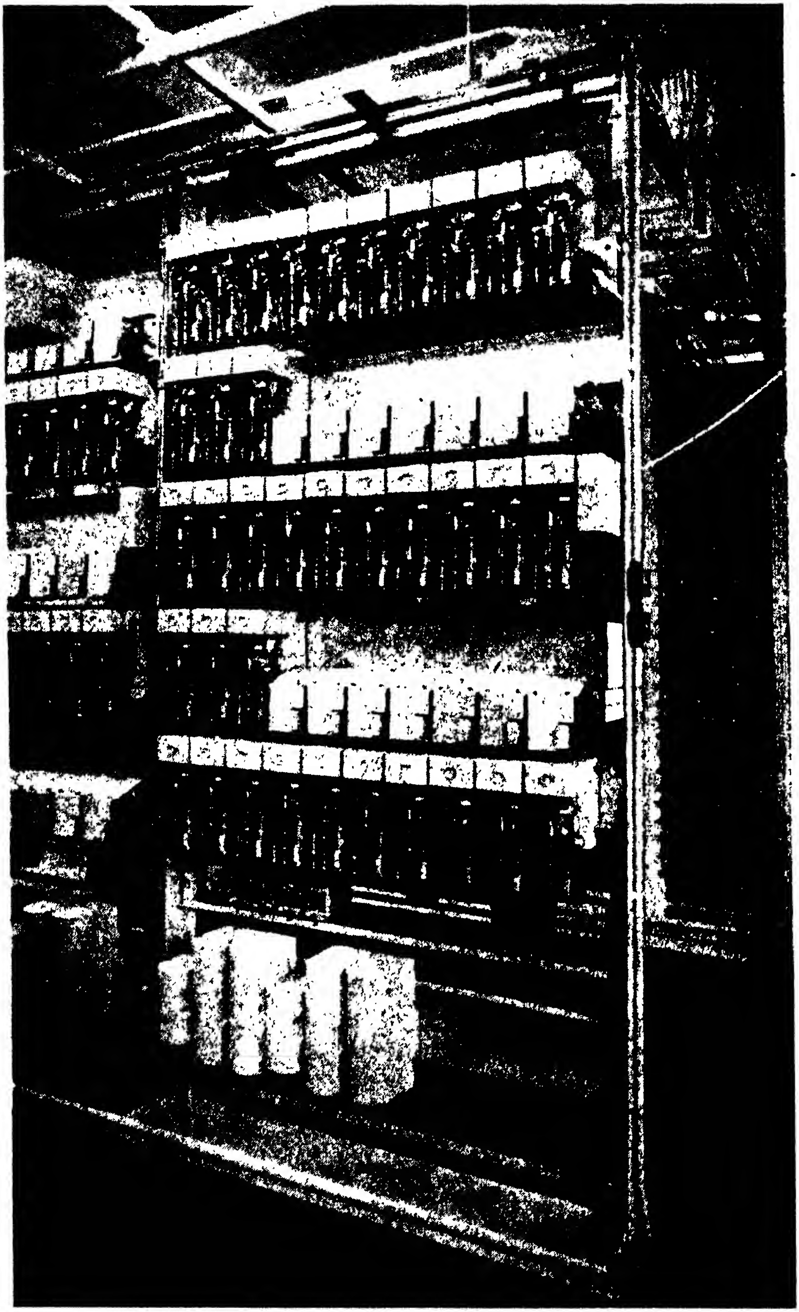


FIG. 217. BAY OF PRIMARY FINDERS
(*Siemens Bros. & Co. Ltd.*)

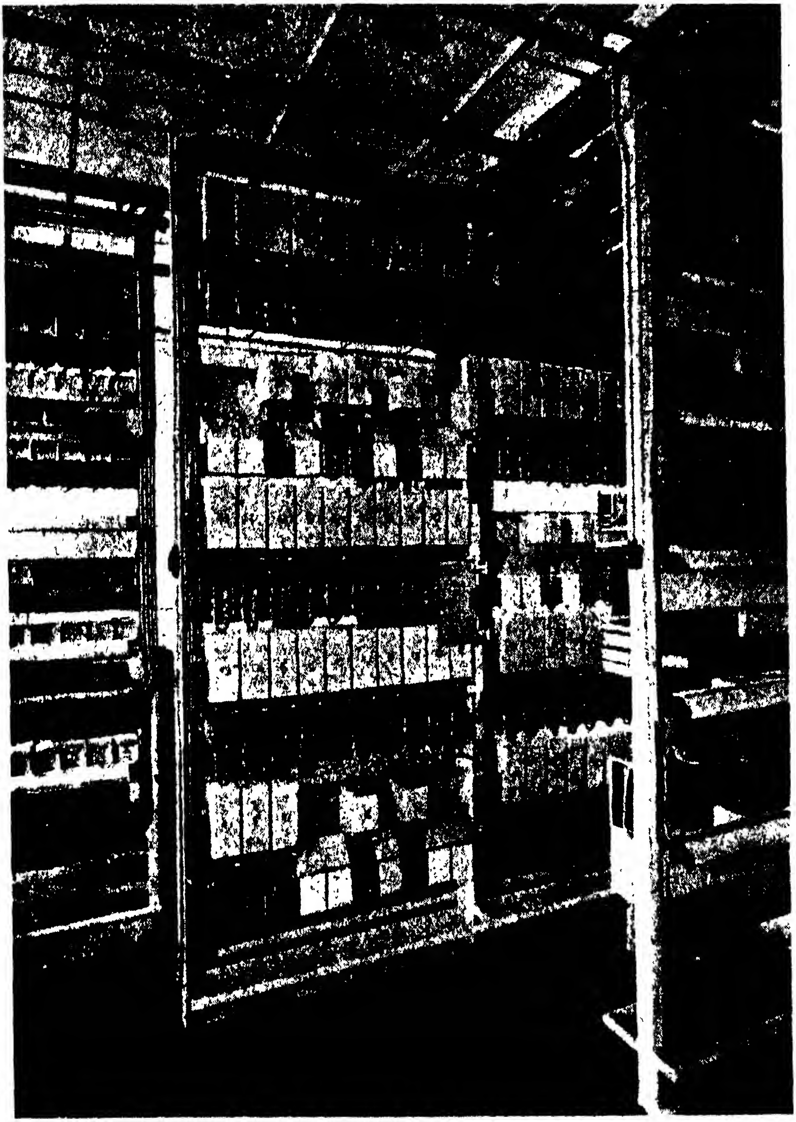


FIG. 218. FINAL SELECTOR RACKS
(*Siemens Bros. & Co. Ltd.*)

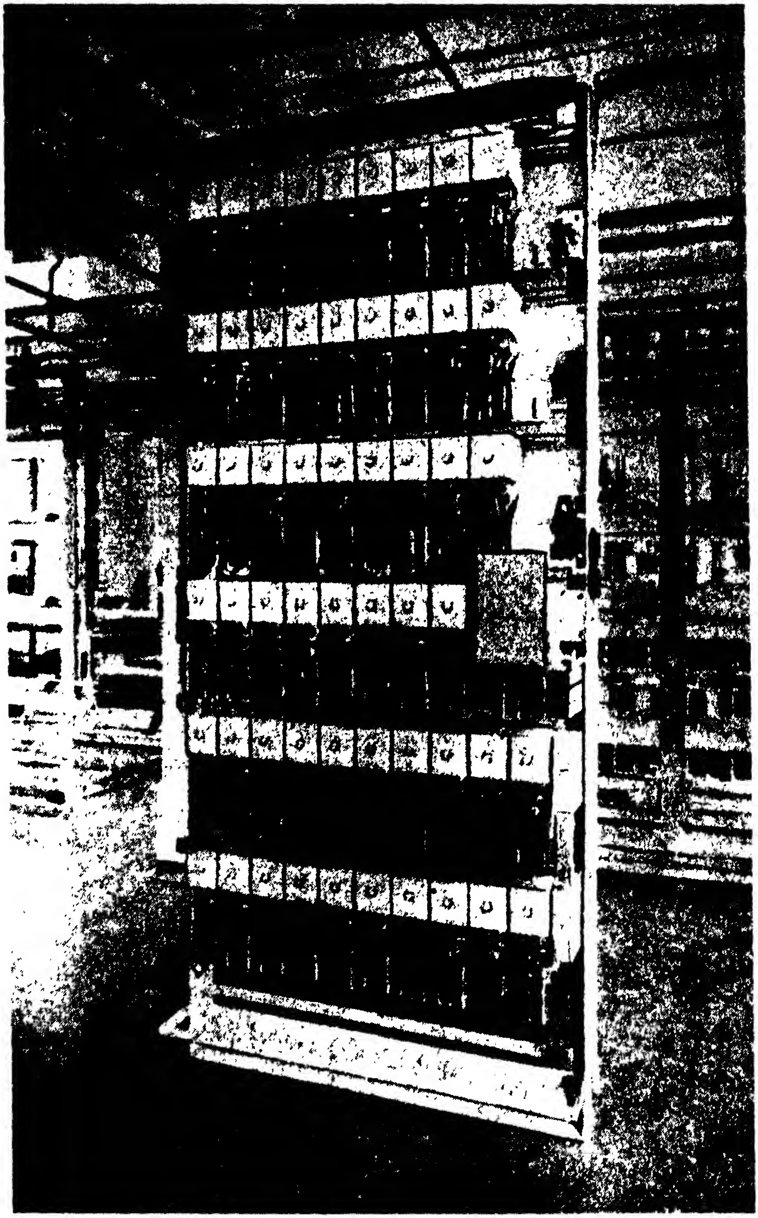


Fig. 219. Numerical Selectors
(*Siemens Bros. & Co. Ltd.*)

The equipment at any automatic exchange must be capable of carrying the maximum load, and at all other stages of loading some, and often most, of the equipment is lying idle.

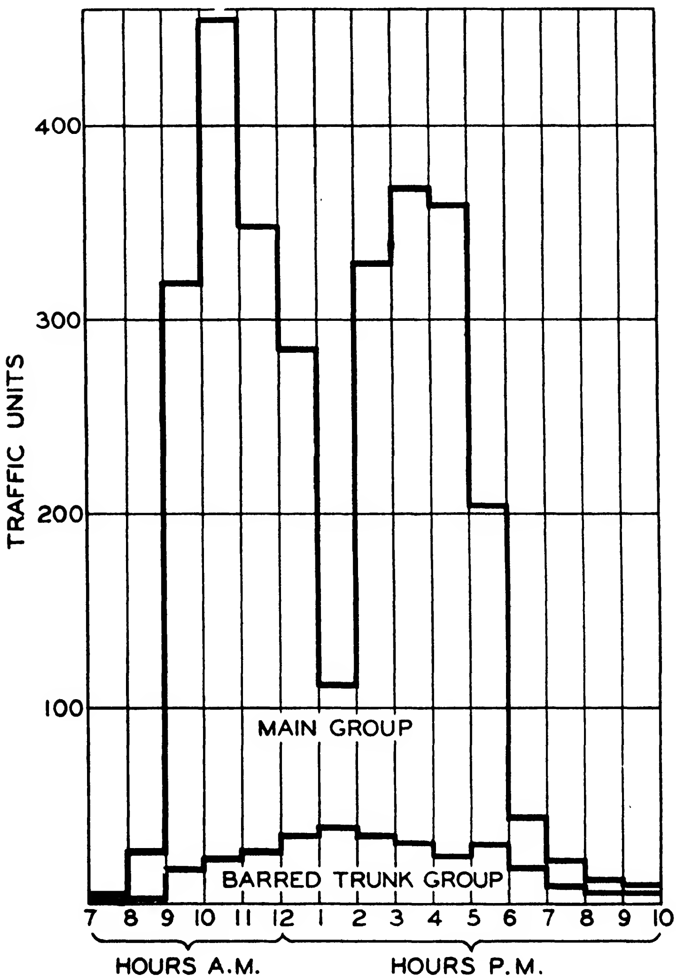


FIG. 220. CENTRAL (MANCHESTER) AUTOMATIC EXCHANGE
Originated traffic; three-day average.

To facilitate the computation of the switch quantities required at each stage of switching, the traffic is assessed in Traffic Units (T.U.'s).

Traffic Unit. This may be defined as follows—

If A be the traffic units;

C be the number of calls in the busy hour;

T be the fraction of the hour taken by a call of average length;

Then $A = C \times T$.

The quantity A can therefore be regarded as the total time occupied in carrying C calls each of an average duration T hours, or as the average number of simultaneous calls in progress during the busy hour.

(Since maximum requirements have to be catered for, the busiest hour is chosen, but the relation of course holds good for any specified period of one hour.)

Busy Hour. A record of the number of simultaneous calls in progress at consecutive periods of say 15 min. during the day, reveals that the maximum load occurs at a clearly defined period or periods, and the 'busy hour' is that period of one hour in which the peak traffic occurs. It will be at a slightly different time of the day in various exchanges, but the fact is immaterial to the computation of the switch quantities. 'Busy hour' conditions are usually met between 10.0 a.m. and 11.0 a.m. in business areas. This period is the only one it is necessary to study, and careful records are taken to discover the average 'holding time' of calls and the average 'calling rate' per line in that period.

Holding times vary from 2·0 to 4·0 min. as a rule, and the calling rate may be as low as 0·2 call per busy hour in a residential area, or as high as 4·0 in a business district.

From these values, the originated traffic may be calculated.

Originating T.U. = No. of lines × Calling rate × Holding time.

To take an example—

Number of subscribers = 5 000

Busy hour calling rate = 1·0

Average holding time = 3·0 min. ($\frac{3}{60}$ hr.)

$$\text{Then originated T.U.} = \frac{5\,000 \times 1{\cdot}0 \times 3{\cdot}0}{60}$$

$$= 250 \text{ T.U.}$$

Capacity of Switches. Any single switch might be occupied continuously by one call during the busy hour, and in such circumstances it will carry one T.U., since C and T each equal unity, and $A = C.T. = 1{\cdot}0$.

This is the maximum load the switch can carry, but will never be realized in service, because when one call has finished the selector will necessarily lie idle until another call is 'offered' to it from a preceding switch, and it is improbable that the waiting time will be zero.

However, if the particular switch is the first of a large group (i.e. connected to contact one of the uniselector or numerical selector banks) it will be offered each call that is passed over the level, and therefore will be occupied for most of the busy period. The actual fraction of the busy hour during which the first or any subsequent switch in a group is occupied when a given number of T.U. is offered can be found from investigations with real or artificial traffic, or may be calculated from the well-known probability formulae (Erlang method). The same results are obtained by either system.

Grade of Service. In extreme circumstances each subscriber might be simultaneously engaged during the busy hour, and, if no calls were to be lost owing to insufficiency of equipment, the number of outlets to first selectors would need to be greater than half the number of subscribers (assuming all the calls were completed locally).

It is obviously uneconomical to cater for this contingency, and the usual practice is to provide sufficient switches so that only one call is lost in each 500 originated during the busy hour. If 20 per cent of the calls per day originate during the busy hour, the overall loss is then only 1 in 2 500, or 0·04 per cent. Of course, the loss only occurs during theoretical peak traffic conditions, and in service may never be realized. Other grades of service, such as 1 in 200, or 1 in 1 000, may be used for design purposes at different stages of switching, since it is obviously of importance whether or not an outlet can be retested once it has been passed over. A uniselector, for instance, repeatedly tests the outlets to which it has access, while a group selector must of necessity give back the busy signal if all the bank contacts are, at the instant of testing, momentarily engaged.

Availability. A subscriber's uniselector has access to only twenty-four outlets to first selectors, and it is not therefore correct to estimate the traffic capacity of a larger group of first selectors than twenty-four without taking into account the fact that all the selectors are not available to any subscriber. To

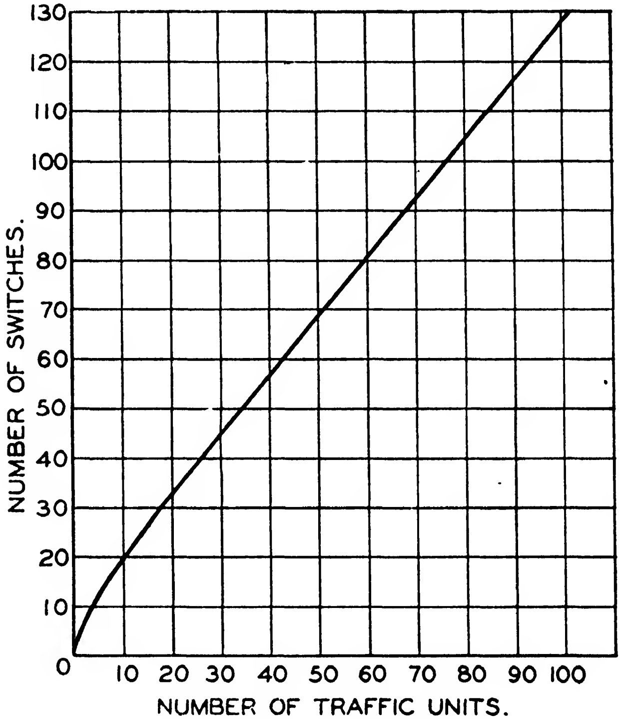


FIG. 221. FULL AVAILABILITY

take an example, forty-eight selectors in a full availability group would carry 32·2 T.U. with a grade of service of 1 in 500; but in two groups of twenty-four, each group would carry only 13·01 T.U.

Where all switches in a group are not available to a calling line, therefore, the number of switches in the group must be increased, so that there is less probability of individual switches being engaged.

'Full availability' is the term used to denote that switches are accessible from all the sources of traffic. Limited availability obtains in cases where more than twenty-four selectors

are associated with subscribers' uniselectors, or more than ten group or final selectors are associated with ten contact banks.

Grading of Outlets. The association of a larger number of switches with a multiple than there are outlets in the multiple implies that the multiple is not 'straight,' i.e. corresponding contacts on different banks are not necessarily connected to the same selector. The surplus switches are distributed over the outlets in a systematic manner, and the multiple is said to be *graded*. As the first contacts of any selector bank will be offered the most traffic, these contacts will carry the greater number of traffic units, and several switches are allotted to the first outlet of a graded multiple, each serving an equal number of banks. The principle is carried through on subsequent contacts as far as desired, the last contacts being commoned together as in a straight multiple. To facilitate the grading of the multiples, the bank outlets are commoned over individual shelves, and then cabled to a Trunk Distribution Frame.

Trunk Distribution Frame (Fig. 222). On this frame (T.D.F.) the outlets from different shelves are arranged so that they may be commoned together or connected to individual selectors as required, circuits in outgoing cables to the next rank of switches being cross-connected to the chosen outlets.

Modern practice is to cable all selector outlets to a T.D.F. so that the loading of the various switches may be varied from time to time to suit changing traffic requirements, without disturbing any permanent wiring.

Small groups of switches are not used as a rule, since it is only practicable to cable individual selectors to outlets multipled at least over one shelf, and unless a reasonably large number of switches can obtain access to a given outlet, the traffic offered to that outlet will not be sufficiently 'smooth' to ensure it carrying its rated load.

Large groups are very subdivided into smaller groups, and separate 'group gradings' are made on the bank multiples.

Examples, showing several typical arrangements, are given in Fig. 223. It will be noted that the switches serving later choice contacts in the bank are multipled over more shelves than those serving earlier choice contacts. This is because the probability of more than one group requiring more than a given

FIG. 222A. TRUNK DISTRIBUTING FRAME
(*Siemens Bros. & Co. Ltd.*)

number of simultaneous calls at the same instant, grows less as the number of simultaneous calls rises.

Traffic Meters. The efficiency or otherwise of the switch provision is verified in service from traffic meter readings. On

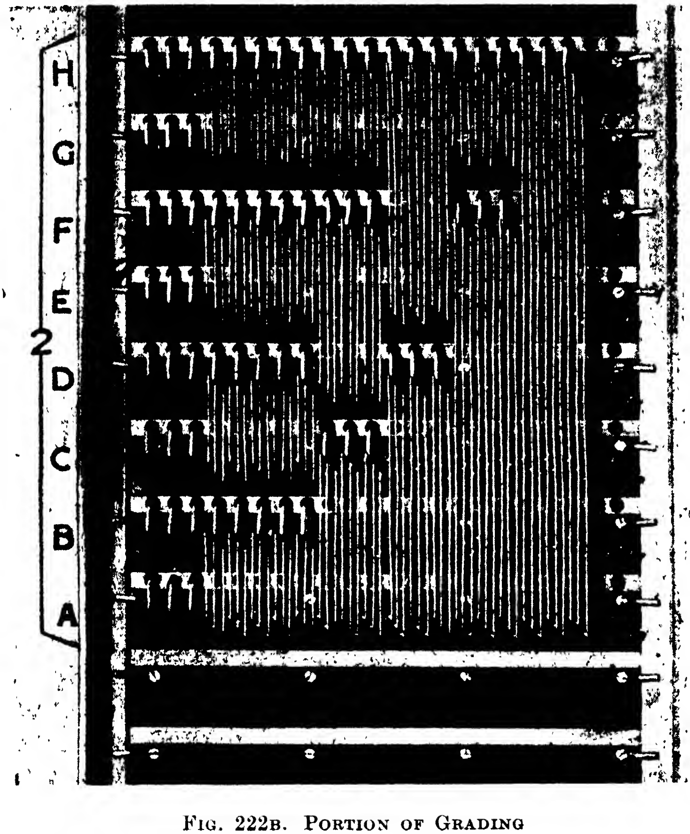


FIG. 222B. PORTION OF GRADING
(*Siemens Bros. & Co. Ltd.*)

the 11th step outlet of each selector level an 'overflow' meter is provided and the switch circuits are arranged so that this meter is actuated each time the level tests engaged. By this means the approximate number of lost calls can be determined, and if it exceeds the grade of service figure, a traffic record is taken. 'Total calls' meters are connected to common apparatus, to give an indication of the total load on the exchange. The switches serving the last outlets of multiples may also be fitted

with 'call count' meters, to give a further indication of the load on the group.

Traffic Recorders. A more recent development of metering is the traffic recorder, which has been designed to measure and record all traffic carried by the various units of automatic apparatus. Connections from the private wires of each switch

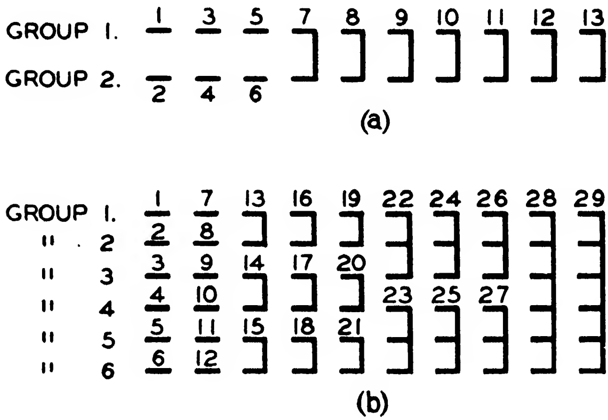


FIG. 223. EXAMPLES OF GRADING

(*a*) Two-group, ten-contact grading with thirteen trunks.
(*b*) Six-group, ten-contact grading with twenty-nine trunks.

in a grading are cross-connected to contacts on the bank of an access selector, and when it is desired to measure the traffic carried by the grading, the access selectors are caused to step at a speed such that each outlet is tested every half-minute where conversation channels are involved, and every 12 sec. where common apparatus is concerned. Meters in the traffic recorder are so connected for each test that they record whether or not particular outlets on the grading are engaged. One meter only is necessary if the total traffic carried is to be recorded, but meters may be connected to single contacts, or groups of commoned contacts, as desired. The number of traffic units is estimated by dividing the number of 'engaged' tests recorded during a period, by the number of tests made. For example, if in 100 consecutive tests a switch was recorded as being engaged 79 times, it would be known to be carrying 0·79 T.U. (since $A = CT$, or $A = 79 \times \frac{1}{100} = 0{\cdot}79$).

Key contacts are provided to steer the recording leads into the particular portion of the equipment it is desired to check. The schematic arrangement is shown in Fig. 224.

Line-finder Scheme. The minimum number of first selectors required for a non-director exchange can be calculated from the known traffic originating from the subscribers. If all the

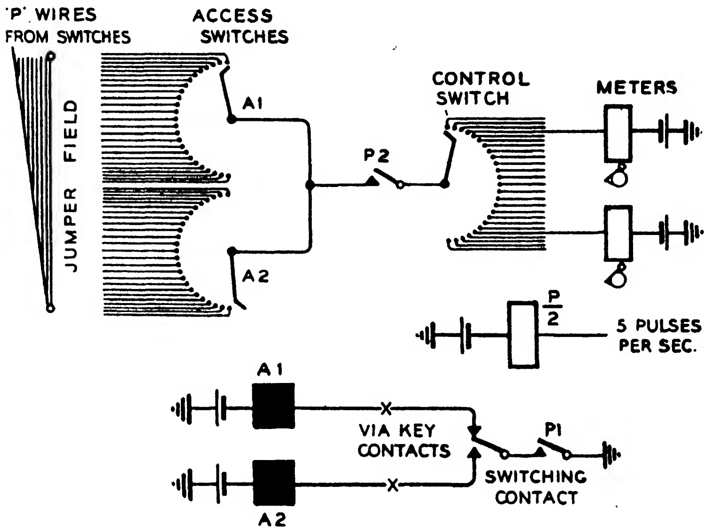


FIG. 224. TRAFFIC RECORDER SCHEMATIC

first selectors were available to any calling subscriber (full availability) this calculated number of selectors would suffice for the grade of service assumed in the calculation.

When each subscriber is provided with a uniselector having only twenty-four outlets, full availability of first selectors clearly cannot be given if more than twenty-four of the latter are required.

In such circumstances, the uniselector bank outlets are graded, and limited availability is given.

If 50-point uniselectors were used, greater economies could be effected, as the size of the groups would be larger, but some wastage would still occur when more than forty-nine first selectors were required.

A solution of the difficulty is to adopt a line-finder scheme, in which the subscribers are divided into groups of 25, 50, 100

or 200, depending on the size of the exchange. In each group there will be a suitable number of line-finder switches, each having access to the whole of the lines in the group. Any one

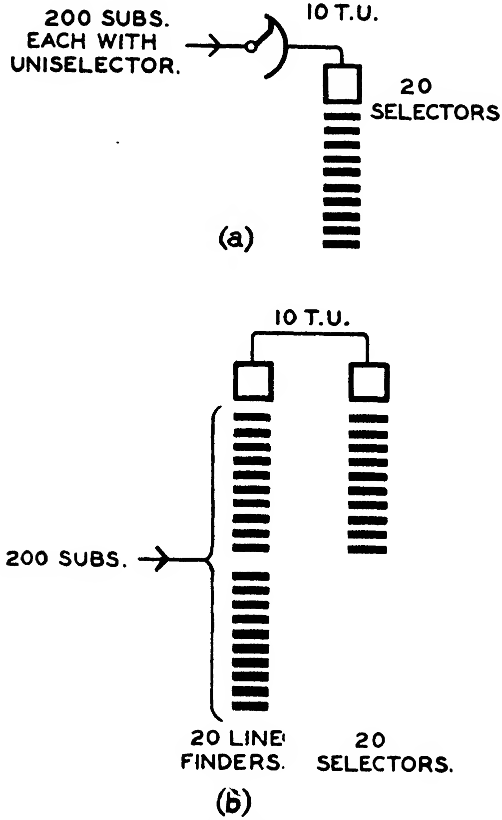


FIG. 225. COMPARISONS OF UNISELECTOR AND LINE FINDER SCHEMES
(*a*) Uniselector scheme. (*b*) Line-finder scheme.
Grade of Service, 1 in 500 in each case.

of these switches may be allotted, and will automatically find the calling party's line when a call is originated.

A first selector will be connected directly to each line-finder and will transmit dial tone to the subscriber as soon as the line-finder has picked up the calling line.

For 25- and 50-line groups, used in U.A.X. installations, uniselectors are connected as line-finders, whilst two-motion selector mechanisms are employed for the 100- and 200-line groups.

Thus, in a group of 200 subscribers' lines, twenty line-finders, connected individually with twenty first selectors, would suffice for 10 T.U. originated traffic, whilst, with a uniselector scheme,

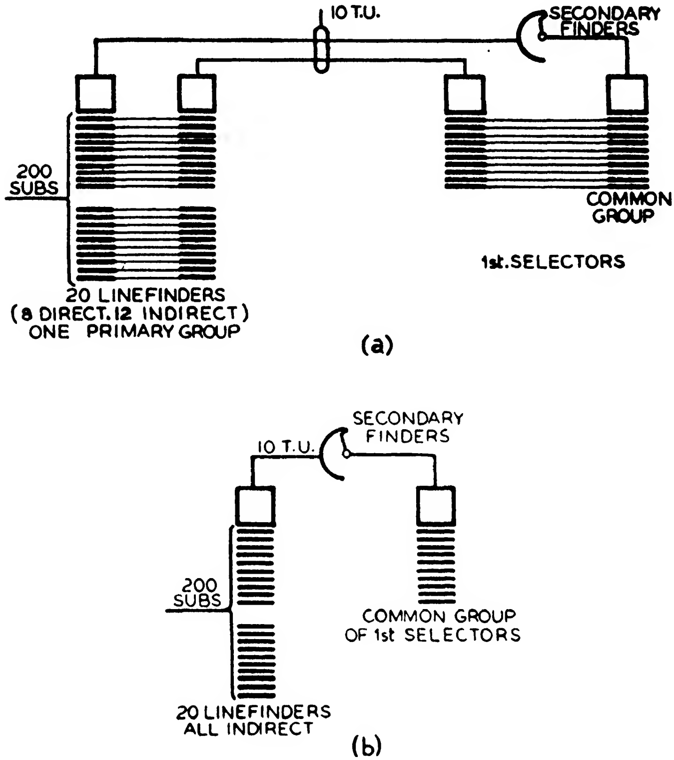


FIG. 226. SECONDARY SCHEMES
(*a*) Partial secondary scheme. (*b*) Full secondary scheme.

200 uniselectors would be needed, each having access to the twenty first selectors. Considerable economy in switch provision is thereby effected, but an examination of the traffic carried by each switch, assuming 10 T.U. per 200 subscribers in the busy hour, will show that the arrangement is far from ideal.

As only one finder is required on each call, free line-finder switches are 'allotted' in turn by a special allotter switch in each group.

Assuming the first free finder in the group of twenty is

allotted to any calling subscriber, the individual switch loads would be (using the Erlang calculation)—

Switch No.	T.U. Carried	Switch No.	T.U. Carried
1	0·91	11	0·51
2	0·89	12	0·44
3	0·87	13	0·36
4	0·85	14	0·28
5	0·82	15	0·21
6	0·79	16	0·15
7	0·75	17	0·10
8	0·70	18	0·06
9	0·65	19	0·04
10	0·58	20	0·02

The first ten switches carry an average of 0·781 T.U., and the last ten an average of 0·217, the latter figure indicating a low efficiency, as would be expected from switches which are only brought into use during peak loads in the group. The first ten switches are being used more efficiently, however, as they will always be offered the bulk of the traffic.

Supposing there are three 200-line groups equipped on the above basis, then thirty of the sixty first selectors required are only carrying 6·51 T.U. between them.

This amount of traffic could be catered for by fifteen selectors, if it were concentrated in one group, and, therefore, by arranging for certain of the line-finders in each group to be connected to first selectors only for the periods during which the permanently connected finders in the same group are all engaged, further economies can be effected.

In the example chosen, ten finders in each group could be connected, directly to first selectors and the remaining ten associated as required with a common group of first selectors by means of a further stage of finding.

The switches which effect this second stage of finding are termed *secondary* finders, whilst the switches in each 200-line group are termed *primary* finders. Each secondary finder is connected directly to a first selector in a common pool, and its bank contacts are cross-connected to selected auxiliary primary finders in the various 200-line groups.

Even in the largest exchanges, 50-point secondary finders

are found to be sufficient, and the uniselector type of switch is therefore used for this purpose.

Under normal traffic conditions, the directly connected (or *regular*) finders can deal with the load, but as soon as they all become engaged, secondary finders having access to the 'auxiliary' primary finders in the congested group, pick up the

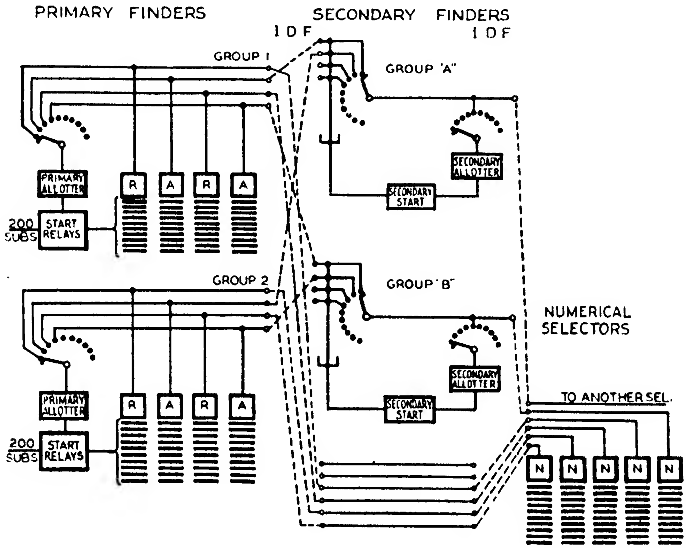


FIG. 227. TRUNKING SCHEME WITH PARTIAL SECONDARY WORKING

R = Regular finder. A = Auxiliary finder.

Other regular finders in each primary group are cross-connected to selectors. Other auxiliary finders are cross-connected to outlets in secondary groups *A*, *B*, *C*, etc., so that each primary group has its auxiliary finders evenly distributed over all secondary groups.

latter and connect them through to selectors. The auxiliary finders then pick up the calling subscribers in the ordinary way. By this means, only the peak traffic from each line-finder group is passed via the secondary finders, and it is the concentration of the peak loads from the individual groups to a common group (or groups) of first selectors that enables these loads to be dealt with so economically.

The characteristics of the traffic (e.g. calling rate, density, etc.) in each group determine the proportion to be routed via the secondary switches, and because the whole of the traffic is not dealt with in this way, the scheme is known as 'partial secondary' working. Still greater economies in first selectors

could be obtained by adopting full secondary working (i.e. connecting all the primary finders to first selectors via secondary finders), but this is outweighed by the increased cost and complication of the controlling circuits, and the fact that the time absorbed in two stages of finding is an undesirable feature when it occurs on every call.

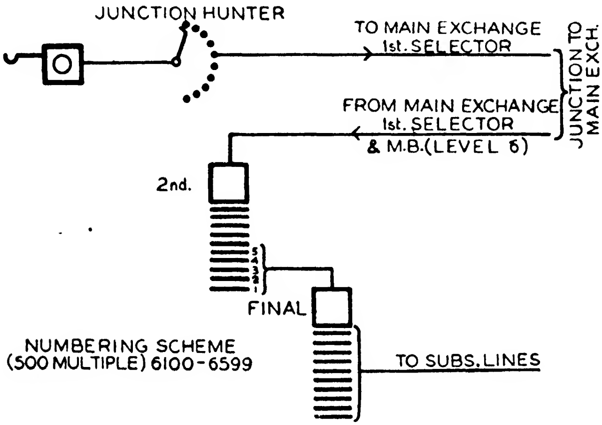


FIG. 228. SIMPLE SATELLITE EXCHANGE

When a call is originated, therefore, the particular line is 'marked' in all the line-finder multiples in the group, by means of the line relay, which also marks the particular level on a vertical marking bank, and starts up the controlling circuits. A free line-finder is chosen by the *allotter switch*, and this line-finder steps to the marked level, cuts in and rotates to the marked contact, and switches the subscriber through to a first selector. If a regular finder has been allotted, the first selector is already connected; but, if an auxiliary finder is taken into use, a secondary start circuit is energized and a secondary finder (with access to the particular auxiliary primary finder) is allotted by the secondary allotter, and connects its associated first selector through to the subscriber via the wipers of both finders. From this point onwards the progress of the call is the same as in an exchange, where subscribers' uniselectors are used.

The regular and auxiliary finders are connected in order to alternate bank contacts of the primary allotter. The auxiliary outlets are automatically 'busied' until all the regular finders

are engaged. The allotter is 'preselecting,' i.e. its wipers always stand on a disengaged outlet in readiness for a call being received.

The present practice is to adopt the line-finder scheme for exchanges where the busy-hour calling rate is below 0·6, and uniselectors where the rate is above 0·6. In the busier exchanges

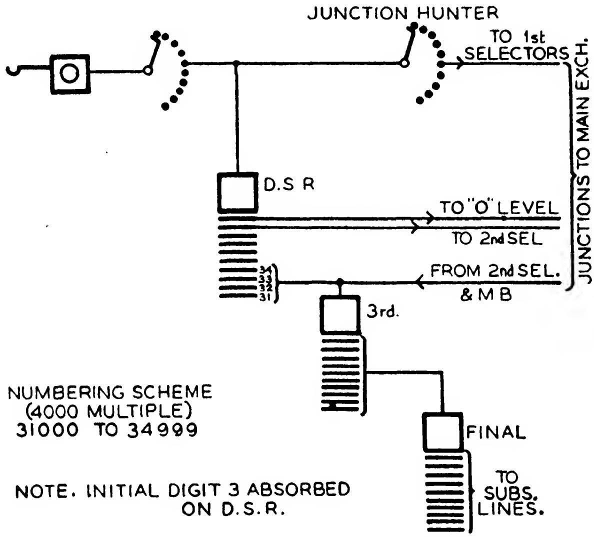


FIG. 229. D.S.R. SATELLITE EXCHANGE

the increased size and cost of the line-finder groups renders the uniselector scheme more economical.

Satellite Working. There are many telephone areas where it would not be economical to concentrate all the switching equipment in one building.

If, in certain portions of the area, there are centres with strong local interest, or districts more or less isolated by some physical barrier such as a river, it may be advantageous to decentralize a portion of the switching plant to serve the subscribers in those districts, whilst still retaining the main exchange switches for completing calls to the remainder of the area.

The term 'satellite' exchange is used to denote an installation capable of concentrating the traffic to and from a given area, and passing it over junctions to the main exchange.

In the simplest cases, satellite exchanges comprise line circuits fitted with junction hunters, which rotate to find a free junction to the main exchange when subscribers originate calls. Relay sets are inserted in the outgoing two-wire junctions to provide a feeding bridge for the subscriber, and to permit metering and holding of the local switch.

The originating traffic from two or three hundred subscribers may thus be concentrated on, say, twenty junctions to the switches at the main exchange, with consequent economies in line plant. Terminating traffic at a satellite of this type is catered for by final selectors thereat, access to these final selectors being obtained from second or third selectors, each terminating a junction from the main exchange. A relay set is inserted in the outgoing junction at the main exchange, so as to provide holding facilities for the main exchange selectors, and metering conditions to the subscribers. There are, therefore, two groups of junctions, incoming and outgoing, between the main and satellite exchanges. Bothway junctions are not used between two automatic switching centres. Several satellites of the above type may be connected to one main exchange, an example being shown in Fig. 230. The numbering scheme for the main and satellite subscribers is determined with a view to making the best use of the available line plant.

At least one digit is needed to step the main exchange selectors on a call to a satellite subscriber. Of the remaining digits, some may be absorbed in subsequent selectors at the main exchange, or all may be repeated to the incoming selectors at the satellite. If from 100 to 1 000 subscribers are ultimately to be connected to the satellite exchange, three digits will be needed to step the selectors in that portion of the switching equipment.

If more than 1 000 lines are involved, the satellite selectors will require four digits, and the numbering scheme for the whole area will be five digit (i.e. one digit at least for the main exchange selectors).

Discriminating Satellites. In the type of satellite exchange mentioned above, a call between two subscribers on the same satellite must be routed via the main exchange, thereby occupying two junctions for the duration of the call. Where there is a large amount of traffic between local subscribers,

Discriminating Selector Repeaters (D.S.R.'s) are used in place of ordinary outgoing repeaters, and local calls are effected without employing external junctions.

The satellite subscribers obtain access, via line-finders or uniselectors, to the D.S.R.'s, each of which is associated with a junction hunter (uniselector). On being seized, the junction hunter rotates to pick up a free junction to the main exchange,

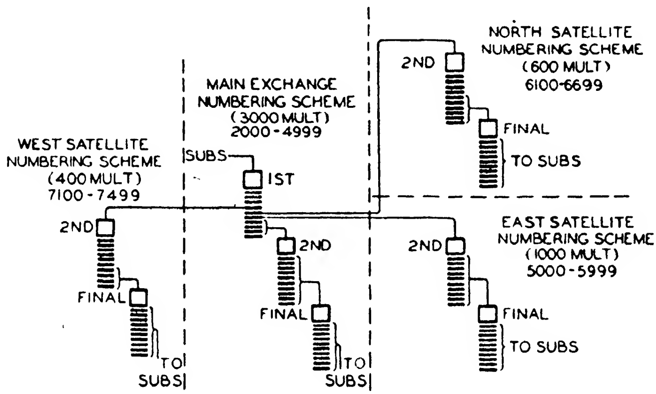


FIG. 230. SATELLITE EXCHANGE AREA

and the main exchange selector terminating this junction steps in unison with the D.S.R. when the calling subscriber dials his first digit. The first digit may determine whether or not the call is to be completed locally. If the D.S.R. wipers are stepped to the level corresponding to the first digit of local numbers, provided the same digit is not used for other exchanges in the area, the junction to the main exchange is released, and the D.S.R. wipers restore to normal. Subsequent digits actuate the selectors in the satellite exchange, the D.S.R. functioning as a second selector. If the D.S.R. is stepped to any other level (except 9 or 0) the selector functions as a repeater, only the main exchange selectors being retained in use throughout the call.

Where the local digit is also used elsewhere, the D.S.R. restores but the main exchange selector does not. The second digit is then dialled, and this will determine if the call is to be completed locally, in which case the main exchange junction is released. This is termed 'discriminating on second digit.'

When 9 or 0 is dialled, the wipers cut in on the level, and pick up a free junction to the main exchange—a junction from level 0 terminating on the manual board, and a junction from level 9 on second selectors at the main exchange. The junction picked up by the junction hunter is released after the first digit has been dialled, and the call is routed over the junction obtained via the selector wipers.

This scheme involves the provision of two additional groups of junctions for the level 9 and level 0 traffic. Since the scheme is only adopted where the number of satellite subscribers is large, and the junction traffic therefore considerable, it is economical to adopt it in most cases, because the ordinary junctions to the main exchange need not provide high grade transmission, whereas the '0' level traffic must be circulated over low-loss conductors. Two grades of junction can therefore be provided, each carrying appropriate traffic.

The incoming traffic to the satellite is carried on one or more groups of incoming junctions, terminating on second selectors. Separate access from the manual board is usually provided, so that the operators may obtain direct connection with satellite subscribers without dialling the initial digit, and over junctions of superior grade where necessary.

Numbering Scheme. The capacity of a 4-digit main exchange, utilizing levels 2–7 for subscribers, is 6 000 lines.

If some of the first selector levels have to be reserved for access to satellites, the capacity of the plant is in general reduced, since each satellite may not need ultimate provision for 1 000 lines, although this block of numbers must be reserved since the initial digit routes the call to the satellite.

The adoption of a five-digit numbering scheme overcomes the difficulty, as each first selector level can accommodate up to 10 000 lines, but four selectors (first, second, third, and final) must be employed to complete each call.

It is only in the largest areas that a full five-digit scheme is economical, and the customary procedure, in cases where a four-digit scheme is insufficient (either initially or ultimately), is to adopt mixed four- and five-digit numbers. The early development, and all the busier lines such as P.B.X's, are catered for by the four digit numbering, but when expansion is needed, certain second selector levels are connected to third

selectors instead of finals, and 1 000 outlets can, if necessary, be obtained from each.

Examples of the various satellite exchange schemes with their numbering ranges are shown in the diagrams (Figs. 228 to 230).

CHAPTER XII

TRUNK EXCHANGES

ORDINARY subscribers' lines are not connected to trunk exchanges, and a somewhat different circuit arrangement is adopted in consequence. In a C.B. manual exchange, the large number of subscribers' lines, on all of which the same service is required, necessitates the use of the minimum equipment per line for economic and accommodation reasons. All the signalling and transmission apparatus is accordingly located in the cord circuits, which are comparatively few in number. As the circuit conditions met on each line are the same, this arrangement is superior from all points of view. In trunk exchanges; the conditions are different. The number of junctions and trunks connected is much less than the number of subscribers' lines would be on a manual exchange with the same number of operators' positions. Further, the type of service given on the different circuits varies considerably, and many signalling and supervisory facilities are required on trunk and junction calls, which are unnecessary on direct calls to subscribers.

On account of these features, and in view of the non-uniformity of the different types of line connected, trunk exchanges are equipped with cord circuits which contain the minimum of apparatus, and all the signalling and supervisory equipment is accommodated in the line terminations, of which different types are provided for the various classes of circuit in use.

The cord circuits simply connect the tip and ring conductors of two circuits straight through. The individual sleeve connections being joined to the cord circuit supervisory lamps.

Thus all supervisory signals are received on the position via the sleeve conductors, and the uniformity of the cord circuit equipment allows full flexibility in staffing, since, as the outgoing and incoming circuits are multipled over all positions, calls may be dealt with by any operator.

This type of switchboard, which is now standard for all except local manual exchanges, has been termed *sleeve control.* The voltage of the standard equipment is 50, thus permitting a

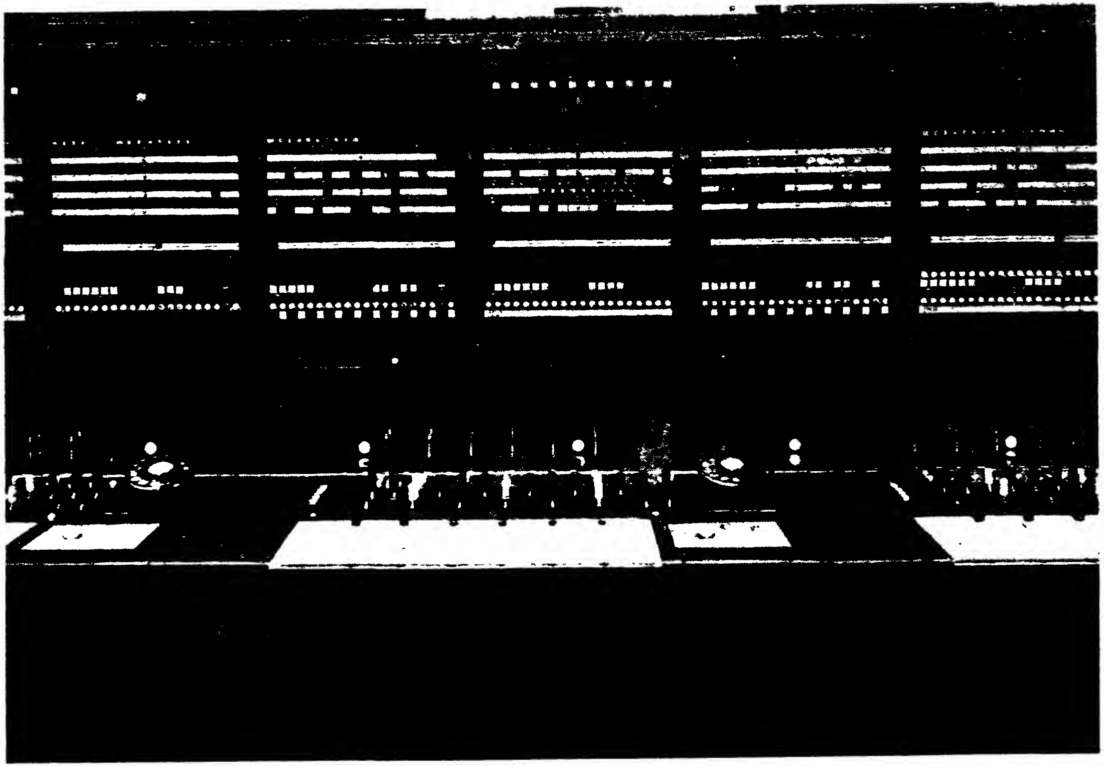


Fig. 231. Trunk Positions
(*Siemens Bros. & Co. Ltd.*)

common battery to be utilized where automatic plant is installed in the same building.

Types of Position. Three types of traffic are catered for at present—'Demand,' 'Delay,' and 'Incoming.' The positions to deal with these classes of traffic are similar in construction, but the panel lay-out is different. 'Demand' positions have an

FIG. 232. TRUNK SWITCHROOM
(*General Electric Co. Ltd.*)

answering multiple in which appear subscribers 'O' or 'TRU' circuits, and the cord circuits are fitted with timing equipment. These positions deal with trunk calls which can be completed without delay, and outgoing pneumatic tubes are usually provided for the dispatch of completed call tickets from the positions. 'Delay' positions are generally 'Demand' positions modified to deal with calls which have been transferred from the 'Demand' switchboard owing to the operator's inability due to insufficiency of junctions or other causes, to complete the call whilst the subscriber waits.

Incoming and outgoing tubes are provided, and there are transfer facilities to allow the operator to accept calls from other portions of the switchboard.

'Incoming' positions deal with calls incoming from other zone or group centres. A special answering multiple for these circuits is provided, and no tubes or timing equipment are required. The same multiple appears over all types of position,

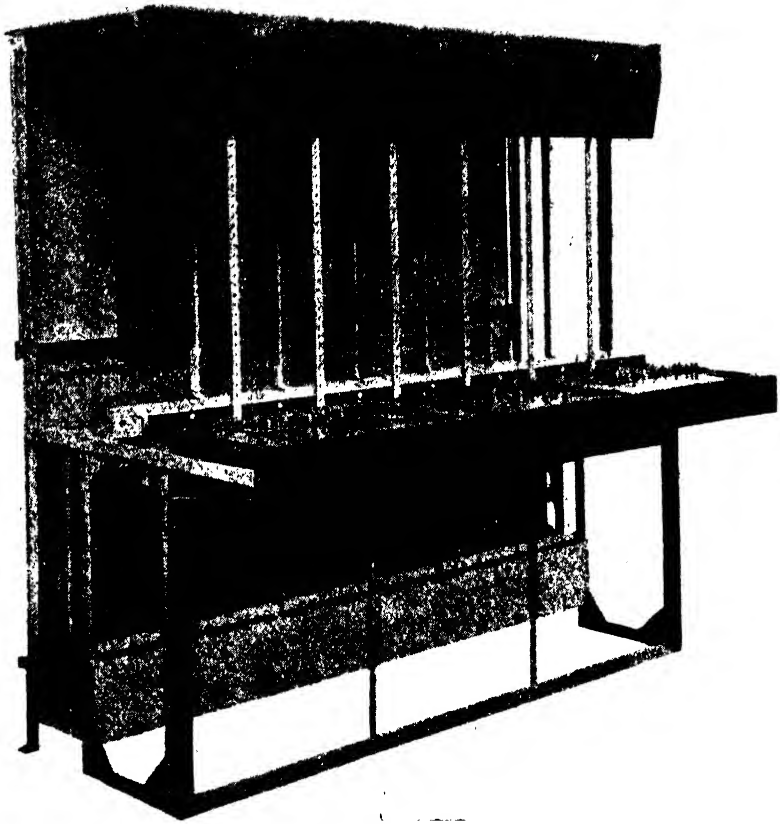


FIG. 233. FRAMEWORK OF SECTION
(*General Electric Co. Ltd.*)

and contains sections devoted to Long Distance Trunks, outgoing junctions with a lamp signal to indicate a disengaged line, and outgoing junctions with ordinary engaged test. A small service multiple is also provided. Views of typical positions are shown in Figs. 231 to 234.

'Demand' System. Calls are completed whenever possible, on a 'Demand' or 'No Delay' basis, and alternative routes are

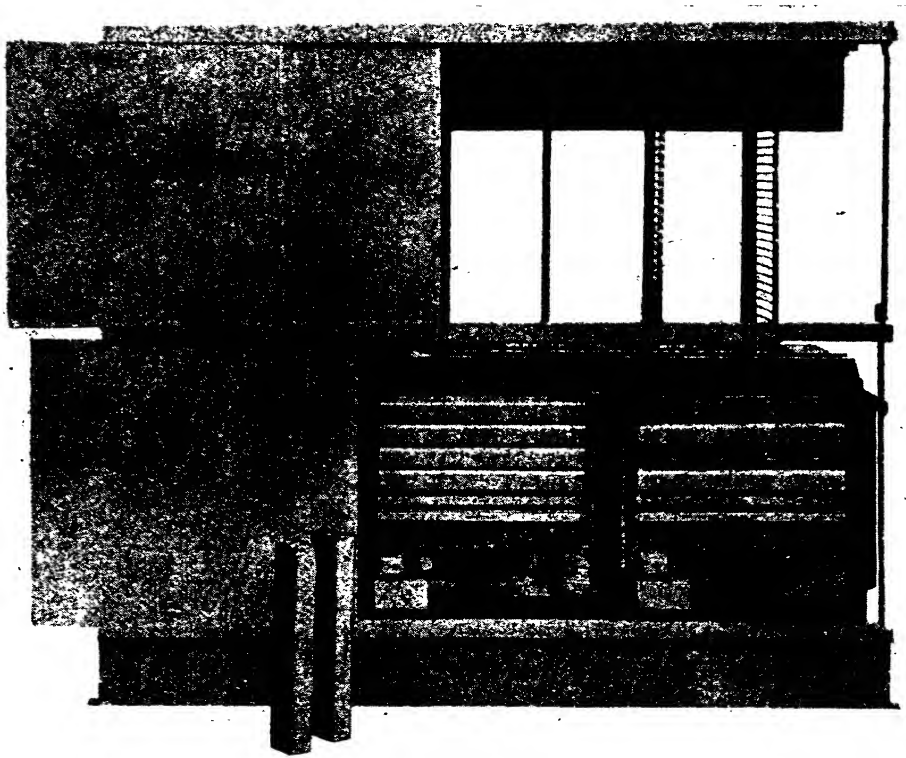


Fig. 234. Rear View of Section
(*General Electric Co. Ltd.*)

selected by the operators if the direct route is busy. Full timing facilities are provided, and are under the control of the calling subscribers' gravity switch, the provision of this facility necessitating the 'reversal' of calls received at trunk switchboards from C.B. exchanges, where the A-cord circuits do not provide through signalling.

If any delay is experienced in completing a connection, the caller is requested to replace the receiver until called.

Under these circumstances, the connection may be held by the operator, who rings back over the circuit to recall the subscriber when the call is ready.

Speed of operation is increased by the adoption of a full answering multiple, in which each circuit appears every four, six, or more panels as desired.

The outgoing trunk multiples are provided with Free Line Signals (F.L.S.), whereby the first idle circuit in a group is indicated by a lamp glow, which is transferred to the next idle circuit as soon as the operator inserts a plug. At zone centres, the cord circuit time check operates a lamp display, and at other sleeve control exchanges a Veeder type clock, associated with each cord circuit, is used to indicate the elapsed time and to give warning signals before the expiry of each three-minute interval.

In a few instances automatic subscribers may need connection to the group or zone centre via a 'minor' exchange, and in these cases forward through signalling facilities are provided over the junctions, so that the timing of the call is still controlled by the calling party.

Circuit Principles. Each operator's position is equipped with one 'Position Circuit' and up to seventeen cord circuits, with any one of which the position circuit may be associated by means of the cord circuit speaking key. The circuits are arranged so that only one cord circuit at a time can be connected, even though more than one key is operated. In the common Position Circuit provision is made for speaking, ringing, and dialling on either answering or calling side, and the cord circuit apparatus is thereby reduced to a minimum.

The items not common to a position are the monitoring keys, and the time check circuits, where fitted.

Answering and calling supervisory lamps are fitted on each

cord circuit, and are controlled via the sleeve conductors of the answering and calling cords, leaving the tip and ring conductors connected straight through, with no bridging apparatus to introduce transmission losses.

Each junction or trunk line terminates in a relay set, which contains a transmission bridge to feed out the correct junction conditions for individual lines, and to translate supervisory

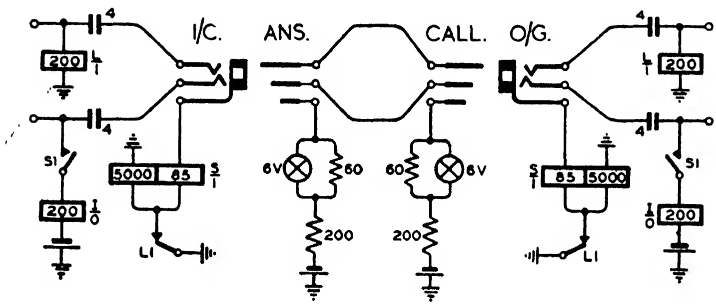


FIG. 235. ELEMENTS OF SLEEVE CONTROL WORKING

signals received over the two-wire junctions into signals on the bush of the switchboard jack (Fig. 235).

Most circuits are worked bothway, and this generally necessitates separate relay sets for the outgoing and incoming portions of the circuit.

Cord and Position Circuit. The outline diagram of the sleeve control cord and position circuit is given in Fig. 236.

The relay SK is operated when the relevant speaking key is thrown, but only if no other key is already operated. In such a case, the common battery feed from the position circuit will be nearly at earth potential, due to the connection of another SK coil, and the second SK relay will not operate. The operation of SK operates SL, and contacts of these two relays split the cord circuit, and connect the tip, ring, and sleeve of the answering and calling sides into the position circuit, from which the various operations can be conducted.

Until the speaking key is thrown, the sleeve conductors are connected to battery via shunted 6-volt supervisory lamps and 210-ohm resistances. The values of the resistances in the circuit allow the lamps to glow at normal brilliancy if the sleeve is earthed through 85 ohms, but will not permit any glow when

earthed through 5 000 ohms. The conditions to be signalled from the junction terminating relay sets, therefore, are—

(*a*) Caller on line—5 000-ohm earth on sleeve.

(*b*) Caller cleared—85-ohm earth on sleeve.

These conditions display the appropriate signals to the operator.

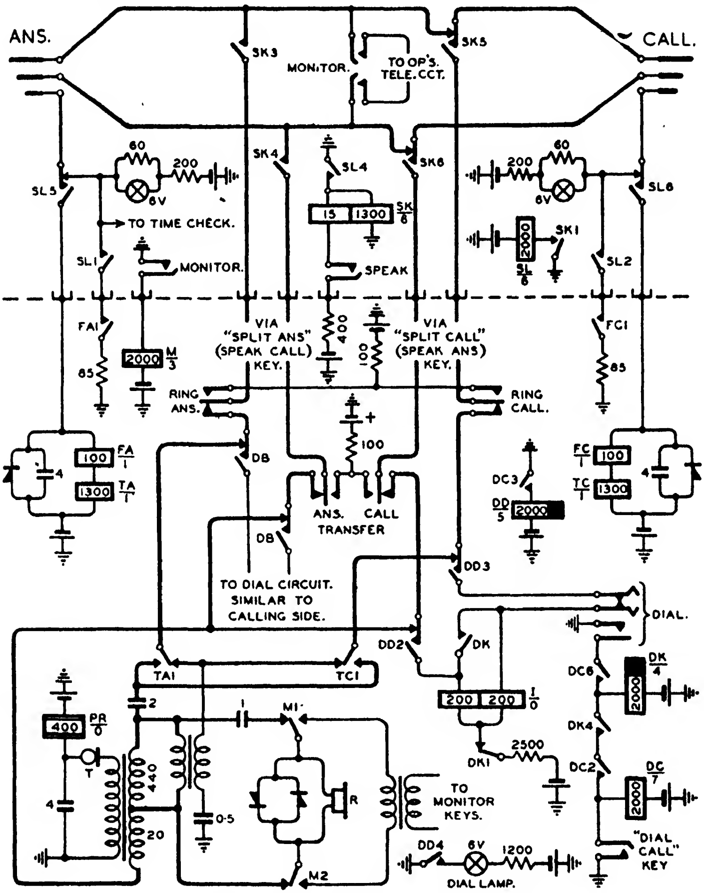


FIG. 236. CORD AND POSITION CIRCUIT

Note. Relay *DB* and certain contacts of *DC*, *DD*, *DK*, and *M* not shown.

Through signalling is effected from one relay set to another, when required, over the ring conductor. The tip conductor is utilized for transmitting the ringing signal into the relay sets, where it is converted into the appropriate calling condition.

When the speaking key has been thrown, and the sleeve

conductors are extended into the position circuit, the answering and calling supervisory lamps are controlled by contacts of relays *AF* and *FC*, which relays are now connected in series with the sleeve conductors, with additional resistance added.

The *FA* and *FC* relays respond to the decrease in sleeve conductor resistance from 5 000 ohms to 85 ohms, and the supervisory lamps therefore respond as before to the junction signals.

The *TA* and *TC* relays now inserted in series operate whenever the relevant plug is inserted in a jack, even if the high resistance sleeve condition is met. Contacts of these relays serve to disconnect the engaged test leads from the common as soon as the plug has been inserted into a jack which has tested free.

The reason for changing the resistance in series to battery on the sleeve of the plug when the speaking key is thrown, is to provide a means of indicating to a distant exchange, when desired, whether or not the operator is on the line. A differential relay in the terminating relay set can be made to respond to the change in resistance in the cord circuit, and relay the signal to the distant exchange.

Ringing. Operation of the RING ANSWER or RING CALL key connects battery via a 100-ohm resistance to the tip of the appropriate plug, thereby actuating the *RR* relay in the terminating relay set. Contacts of this relay apply the correct ringing condition to line.

Dialling. This is effected by operating the DIAL ANSWER or DIAL CALL key. Assuming the latter key is operated, relay *DC* in the position circuit is energized.

DC operates *DD*, which removes the operator's loop from the line, and allows *DK* to energize as soon as the dial is pulled off normal.

Contacts of *DK* provide a clear impulsing loop until the dial returns to normal. Until the dial key is restored, the 'dial' lamp glows to remind the operator that the circuit is disconnected from the speaking set. Other contacts of the relays concerned prevent premature operation of switching relays in outgoing relay sets, since the transmission bridges must of necessity be cut out during the sending of loop impulses.

Transfer Facility. The operation of the transfer key connects positive battery to the ring conductor, and on relay sets terminating certain classes of circuits, this battery will operate a relay which will transfer the calling signal to another suite of positions.

Monitoring. The monitoring key operates relay *M*, and the operator's receiver is thereby connected across the secondary winding of the monitoring transformer, the primary of which is connected across the tip and ring of the cord circuit.

The primary has a high impedance, and therefore does not introduce a serious transmission loss.

Coupling. A key is provided whereby the operator may couple a position to the adjacent position on the right during slack periods.

Speaking Circuit. As previously mentioned, the engaged test circuit is completed when the speaking key is operated, from the tip of the cord circuit plug via the *TA* and *TC* contacts, to a common winding on the operator's position transformer. The insertion of a plug into a jack, with the speaking key thrown, results in the operation of *TA* or *TC*, and the circuit is broken. When the speaking key is restored, the test commons are disconnected at contacts of relay *SL*.

With the speaking key operated, the operator's circuit is connected across the tip and ring of the cord circuit, either side of which may be cut off at will by the operation of the 'splitting' key—marked SPEAK ANSWER and SPEAK CALL.

When the calling side is isolated by the operation of the SPEAK ANSWER key, and vice versa, a 600-ohm resistance, with a 1 μF. condenser in series, is connected across the tip and ring of the disconnected cord, so that the line may be terminated by a suitable impedance, to prevent self-oscillation in the repeaters. This impedance is frequently used in terminating relay sets also, and is termed the *anti-singing* impedance.

The sleeve circuits are shunted by rectifiers and condensers to absorb induced voltages on withdrawal of the plugs. The disposition of the cords and keys is shown on the lay-out diagram for the keyshelf (Fig. 237).

Timing. At most zone centres, a lamp display per position is fitted in the panel in front of the operator. The throwing of any cord circuit time check key to the START TIME position

connects a stepping circuit from a 12 sec. pulse to a uniselector (one per time check), which makes one step each 12 sec. as long as the calling subscriber is on the line. By restoring the key, the elapsed time is indicated on the lamp display, 12 sec. prior to the expiry of each 3-min. period, the time check lamp glows, and three 'pips' of 900-cycle tone ('time announcing'

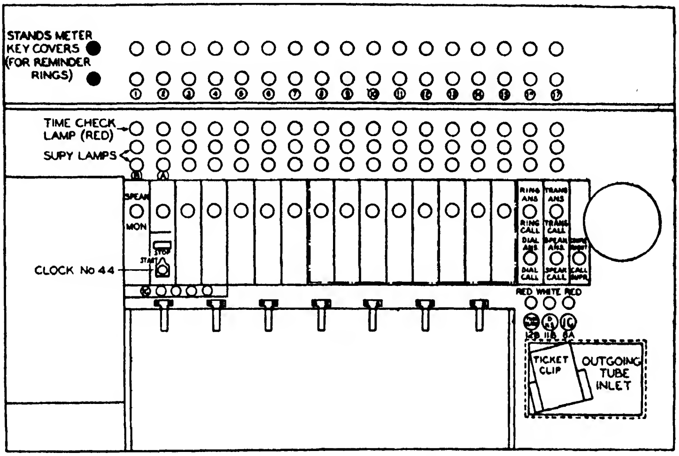


FIG. 237. KEYBOARD LAY-OUT

signal), are transmitted to line, to warn the subscriber that the unit period has elapsed

On other sleeve control switchboards, a Veeder type clock is used in place of the timing uniselectors, and gives a direct indication of the time during which the caller has been on the line. The time announcing signal is also given with this system of timing, the operation of which is as follows (Fig. 239).

When the trunk operator has connected the caller to the desired line, the rotary key of the Veeder clock associated with the cord circuit in use, is turned to the START position, operating the sets of springs marked START KEY. Relay *S Y* is operated once every 6 sec. by the earth pulse from a *TP* relay, but only so long as the calling party is on the line. Should he clear, the low resistance earth placed on the sleeve of the answering plug shunts *S Y* and prevents its operation. Since *S Y*1 steps the clock magnet, the timing of the call is controlled by the subscriber's gravity switch. The clock mechanism is actuated

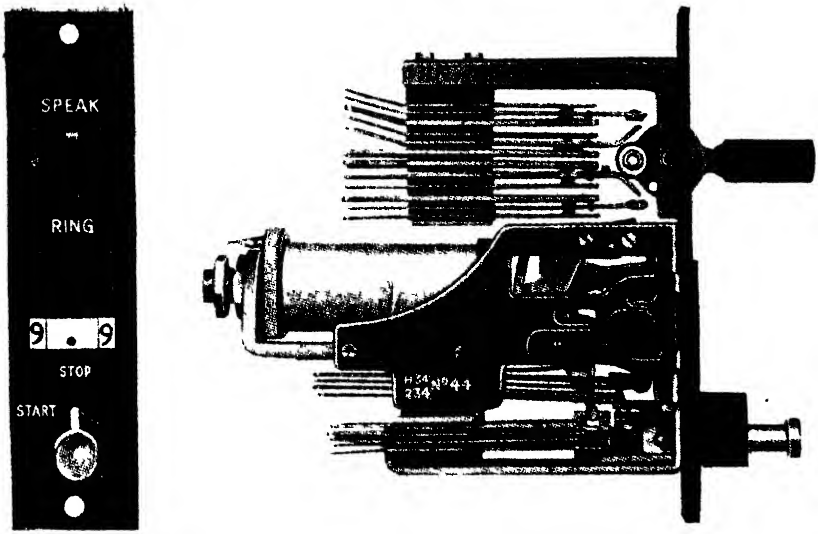


FIG. 238. TIME CHECK CLOCK MECHANISM

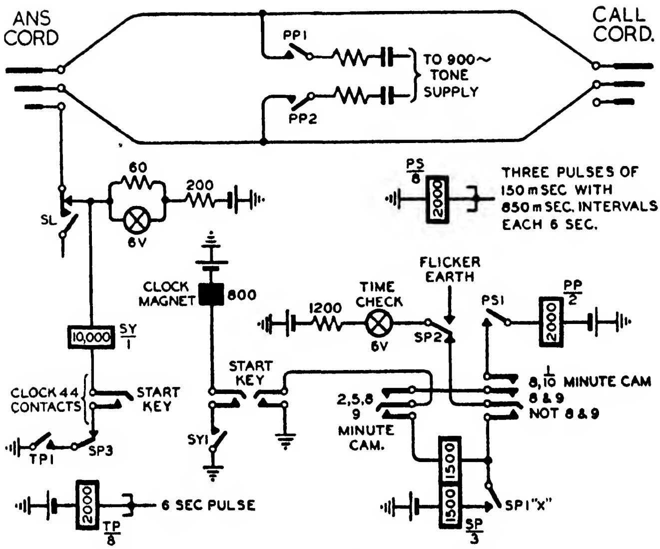


FIG. 239. TIME CHECK CIRCUIT
Spring figures indicate make times.

every 6 sec., and the number discs show the elapsed time on the keyboard of the position. After 2·8, 5·8, and 8·8 min., a circuit is completed via the cam springs for the *PP* relay, which pulses at *PS*1 and transmits the time announcing signal to the caller. The time check lamp also glows to advise the operator that a 3-min. period is about to be completed. At the end of 9 min., if the call is still in progress, *SP* operates and flicker earth is connected to the time check lamp, whilst the clock pulsing circuit is broken at *SP*3. If further timing is required, the

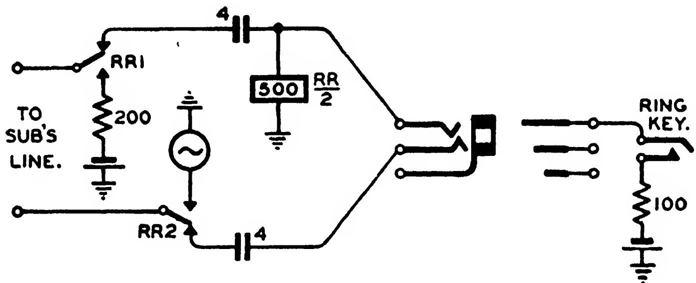


FIG. 240. RE-RING CIRCUIT, MAIN EXCHANGE

operator depresses the RESET plunger, and a second 9-min. period is commenced, the mechanism being first returned to normal. The operator may stop the timing at any stage by turning the rotary key to the STOP position, thus arresting the stepping of the clock magnet.

Routine test facilities are provided for rapidly verifying the correct functioning of the clocks. The 0·2 sec. flicker earth is used, instead of the 6 sec. pulse from the electric clock, to operate the *S Y* relay of the circuit under test.

The 900-cycle tone is produced by a valve oscillator, and the stepping of the switches and keyboard clocks is controlled by a master electric clock.

Terminating Circuits. (*a*) DEMAND CIRCUIT. This circuit is described in the "Automatic" section. It is used to terminate lines from the '0' levels at non-director exchanges. An outline diagram showing the re-ring feature is given in Fig. 240.

In areas where the manual board is remote from the automatic exchange, a different circuit is used, providing 'manual hold' over the positive wire of the junction, and 're-ring' over

the same wire by utilizing a positive battery and a rectifier across the re-ring relay at the distant end.

A similar arrangement is used in the relay sets terminating junctions from satellite exchanges (Fig. 241).

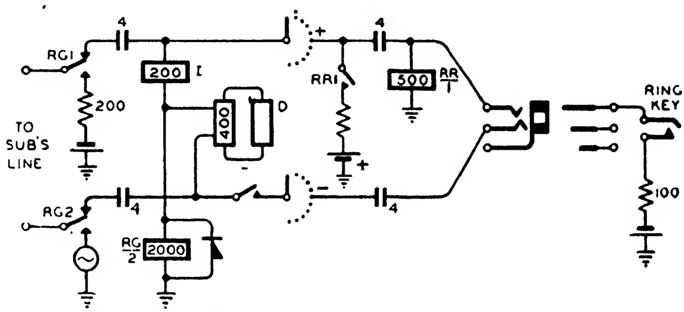


Fig. 241. Re-ring Circuit, Satellite Exchange

(*b*) Record Circuit. Trunk calls from subscribers connected to C.B. exchanges are received over 'record' circuits.

Details of the subscriber's requirements are taken by the trunk operator, who then proceeds to 'reverse' the call, by

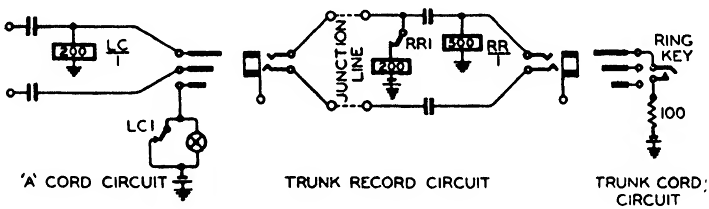


Fig. 242. Record Circuit with Flashing Facility

calling the originating subscriber over an outgoing junction to the B-operator at the C.B. exchange.

This B-operator is asked to 'overplug' the required line (i.e. ignore the engaged test), and the original connection via the A-operator is then cleared down.

This procedure is necessary because the A-cord circuit does not transmit a through clearing signal, and it is essential that the timing equipment in the trunk cord circuit should be under the control of the calling party's gravity switch.

A similar procedure is adopted on calls incoming from dialling-in manual exchanges.

An outline of the circuit is given in Fig. 242, showing how

the trunk operator's ringing key may be used to 'flash' the A-operator when required.

Outgoing Junction Automatic Signalling (Fig.243 (*a*)).—In this circuit, standard C.B. conditions are fed out to the distant exchange when the calling plug is inserted in the outgoing jack. An earthed relay on the A-line receives the answering signal from the distant end, and converts it into a supervisory signal on the cord circuit lamp via the sleeve conductor.

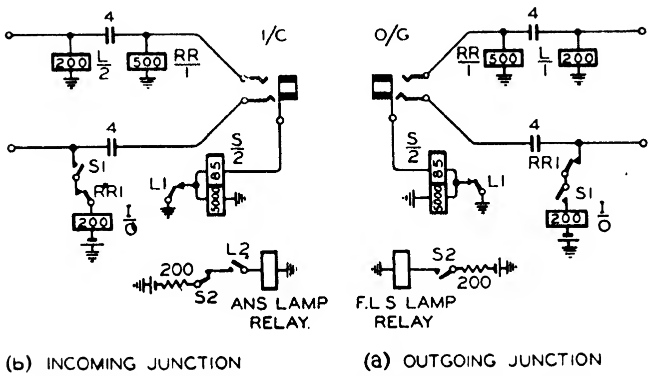


Fig. 243. Outline of Automatic Signalling Circuit

Incoming Junction Automatic Signalling (Fig. 243 (*b*)).—An earthed relay on the B-line receives the signal, and operates the lamp relay, which in turn causes all calling lamps on that particular circuit to glow. The insertion of an answering plug into the jack extinguishes the lamps, and returns supervisory battery on the A-line of the junction. The distant operator may be recalled by operation of the position circuit ringing key, which results in the disconnection of the battery to the A-line.

Bothway Trunk, Generator Signalling (Fig. 244). On incoming calls, the generator ringing is received on the L-relay, which is shunted by a rectifier to improve its response. The calling lamp relay is locked in until the operator answers, owing to the intermittent nature of the calling signal. On outgoing calls, operation of the cord circuit ringing key results in the transmission of a.c. ringing to the line. The distant operator may be recalled by the same means, the circuit being arranged so that once the

plug is in the jack, momentary receipt of ringing current causes the supervisory lamp to flash continuously until the operator throws the speaking key. No through signals or automatic clears can be given on this class of circuit.

500-cycle Ringing. On most trunk circuits, the low frequency a.c. ringing is converted to 500-cycle a.c. at the first repeater station on the route, and converted back into alternating current of low frequency at the last repeater station.

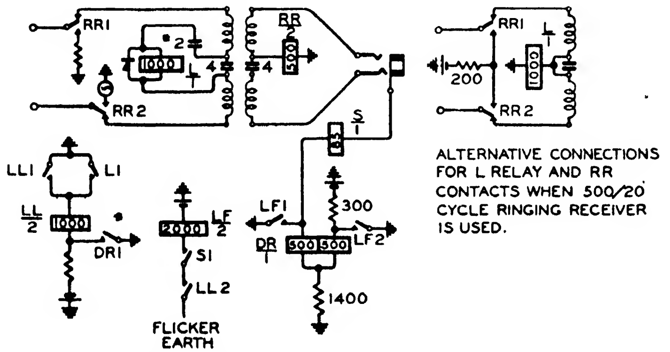


FIG. 244. GENERATOR SIGNALLING TRUNK CIRCUIT

This is necessary, since the telephone repeater will not transmit signals of such low frequency as exchange ringing. Where the terminal repeater station is in the trunk exchange, the 500-cycle currents in the trunk line may be converted into direct current for signalling to the trunk switchboard, and vice versa, thereby simplifying the signalling circuits. The outline diagram of a relay set which performs this function is shown in Fig. 245.

Battery is connected to the valve circuits continuously, and all line currents are picked up and amplified by the first valve, which is a triode, biased positively on the grid. The resistances in series with the transformer winding reduce the tapping loss to a minimum, and the centre point connection of the *RL* relay permits its actuation from the position circuit without unbalancing the line. On outgoing calls, the operation of *RL* by the ringing key disconnects the receiver and switchboard termination, and sends out 500/20 cycle ringing to the line, at a level determined by the value of the series resistances (usually at + 3 db.).

When an incoming ring is received, the triode amplifies the signal, which is then impressed on the grid circuit of the pentode valve. The input to this valve is from a series circuit tuned to resonate at 500 cycles per sec., and only at this frequency will any input voltage produce an appreciable potential difference

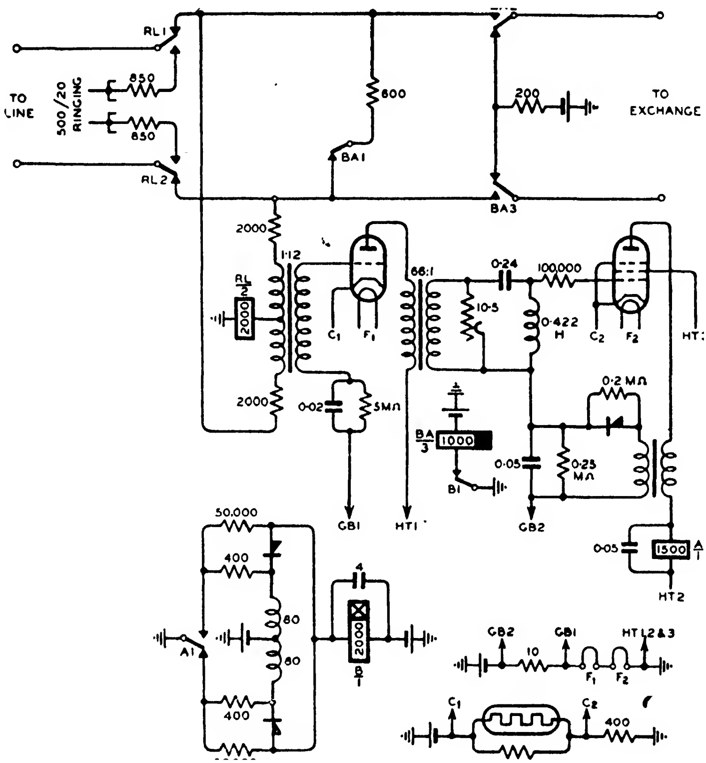


FIG. 245. 500/20 CYCLE RINGING CONVERTER

across the inductance bridging the grid and cathode. The majority of speech signals therefore do not tend to actuate the pentode. The condenser and resistance in the grid circuit of the triode act together with the positive bias, as a voltage limiter, since when the input exceeds a certain value, the resultant increased flow of grid current through the resistance biases the valve more negatively, thereby reducing its amplification. By this means a reasonably constant input to the pentode is assured. The pentode is biased negatively so that

normally no appreciable anode current flows, but when a 500-cycle signal arrives, alternate half-cycles are rectified on the anode bend principle, anode current flowing during each positive half-cycle, charging the condenser across the A-relay and operating the latter once for every train of 500 cycle pulsations. Since the ringing is interrupted twenty times per second, the A-relay will pulse twenty times per second on the receipt of this signal, but will operate only intermittently on speech input at the same nominal frequency. The rectifier and transformer in the anode-grid circuit serve to apply 'rectified reaction' to the valve, and any input above a certain minimum valve acts as a 'trigger,' making the output build up rapidly to a constant value, until the input signal ceases. The pulsing of the *A*1 contact at 20 cycles per sec. creates high induced negative voltages across the terminals of the inductance, and therefore across the B-relay, since the rectifiers normally prevent any flow of current through the coil from the 50-volt battery. Relay B will therefore operate if *A*1 pulses consistently, but not if it only operates intermittently, since the 50 000-ohm leak resistances allow a reverse current to flow in the B-relay coil during a permanent make or break of the *A*1 contact. This feature, together with the slug on the core, and the 4 μF. condenser in parallel, gives the discrimination necessary between ringing and speech inputs, and prevents the production of false signals. *B*1 releases *BA*, after a further lag of 250 msec., to provide an additional safeguard against false operation. *BA* contacts disconnect the local side of the circuit, and give a d.c. signal to the terminating relay set, and thereby lighting the calling lamp, or, if the call has already been set up, giving a 'recall' flashing signal on the cord circuit supervisory lamp. An anti-singing impedance is connected across the lines when the switchboard side is cut off on receipt of a ring, and it will be noted that the receiver is energized entirely from the 50-volt battery, and that a ballast resistance is used to correct for any variations in the exchange voltage.

Through Signalling. This facility can only be given over automatic signalling junctions. The schematic arrangement is shown in Fig. 246. It will be noted that differential relay *DR* is used to detect the operation of the cord circuit speaking key. Normally, the currents in the two windings are equal and have

opposite magnetic effects, but when the speaking key is thrown, the current in one winding is diminished owing to the greater resistance inserted in series, and the relay operates, restoring again when the speaking key is returned to normal.

Relay *DR* controls the operation of *TS*, over one winding of the latter. The second winding is in the ring circuit, and receives current from the relay set on the other side of the cord circuit only when the distant party is on the line.

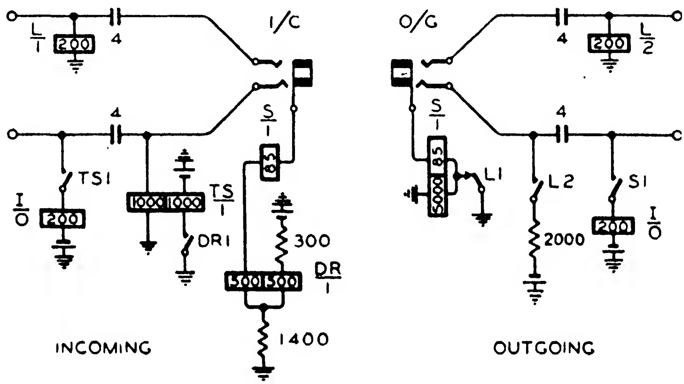


FIG. 246. OUTLINE OF THROUGH SIGNALLING CIRCUIT

Hence the *TS* contact, by applying supervisory battery to the A-line of the junction, controls the through signal.

Forward Through Signalling. Some auto-manual switchboards are not situated at group or zone centres, and the control of the call is not then vested in the operator who first answers the subscriber. The terminating relay sets for the '0' level calls, and for the circuits outgoing to the group or zone centre, are equipped with facilities for 'forward through signalling,' i.e. the subscriber's gravity switch controls the supervisory signal and timing equipment at the second switchboard, the first operator merely setting up the connection and awaiting clearing signals.

Fig. 247 shows the connections. So long as the subscriber is on the line, *L* is operated, and both coils of *CL* are in series, allowing insufficient current to pass to operate *TS* in the outgoing relay set, when the latter is connected. Should the subscriber clear, *TS* operates to the reduced resistance, and removes the supervisory battery from the trunk line, connecting

an earthed re-ring relay RR, in its place. If the distant operator, who now gets the clearing signal, wishes to recall the subscriber, battery is sent out to operate RR, which relays the signal over the tip conductor into the '0' level relay set, causing ringing current to be sent out to the subscriber's line. A clear is not given to the local operator until both sides of the circuit are disconnected, since L in the outgoing relay set

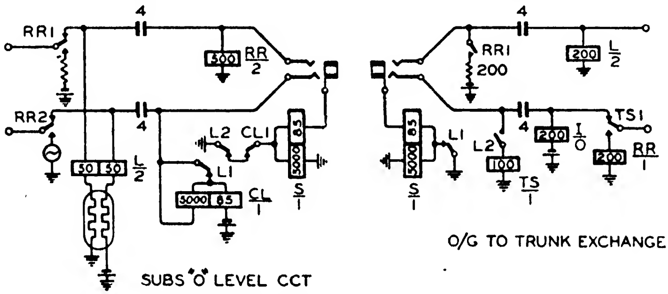


FIG. 247. FORWARD THROUGH SIGNALLING

retains CL operated, and prevents the short-circuiting of the 5 000-ohm coil of S on the answering side.

Transmission Bridges (Fig. 248). Impedance coils and condensers are used to form the transmission element on all except long distance trunk circuits, where the superior impedance balance required is obtained by means of repeating coils. Since the various signalling conditions, often involving the use of discriminating resistances, have to be applied through the impedance coils, steps are taken to ensure that the balance is not upset by any change in circuit resistance. This is accomplished by connecting a large condenser between the inner ends of the impedances, thereby rendering the impedance to earth similar for each line.

'Dry' contacts in the circuits are avoided by the use of very high resistances placed across the condensers, thereby allowing currents to flow which will be too small to affect the relays, but will prevent the production of noise at contacts which would otherwise carry no current.

(The above features have not been included on the various outline diagrams, in order to simplify the connections.)

Free Line Signals (F.L.S.). The outgoing trunk multiplies, and some outgoing junction multiples, are equipped with

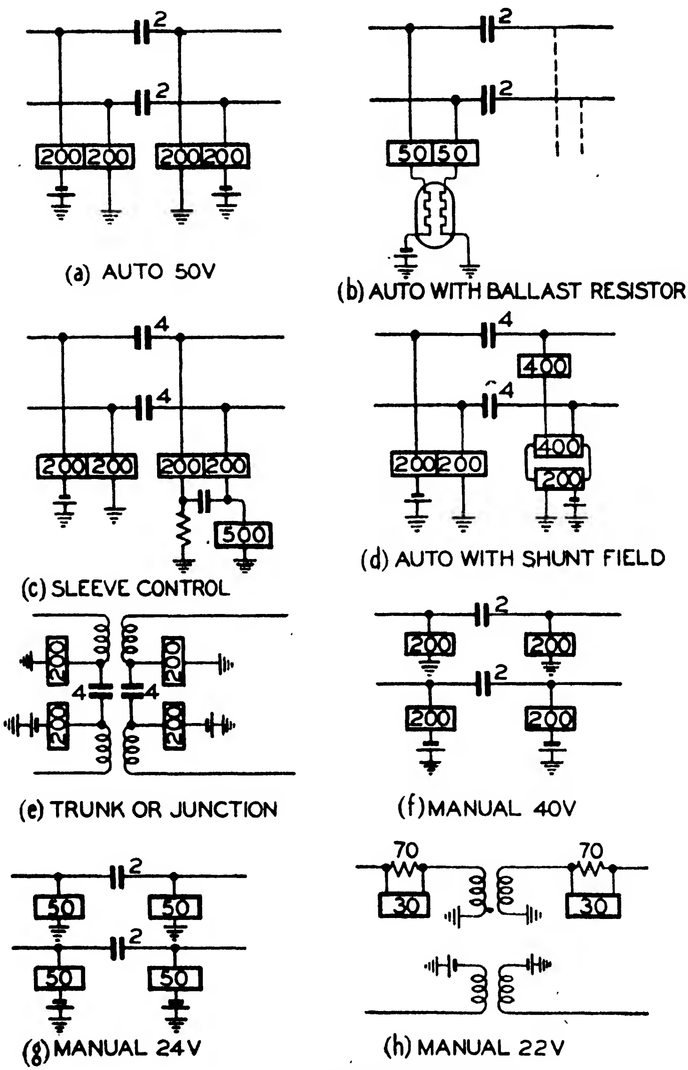


FIG. 248. TRANSMISSION BRIDGES

F.L.S. As each circuit is taken into use, a relay operates and transfers the battery connection to the lamp corresponding to the next free circuit in the group. As any circuit becomes free, the release of the corresponding relay will cause the lamp signal

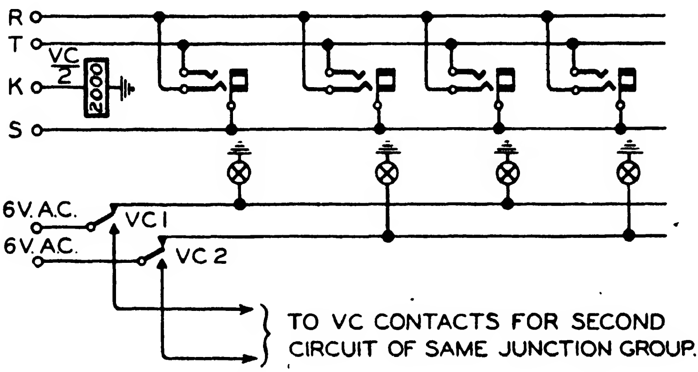


FIG. 249. MULTIPLE JACKS WITH FREE LINE SIGNAL (F.L.S.)

to revert to that circuit if it thereby becomes the first free line in the group. By this means operators do not need to make the engaged test when finding a disengaged line, although the

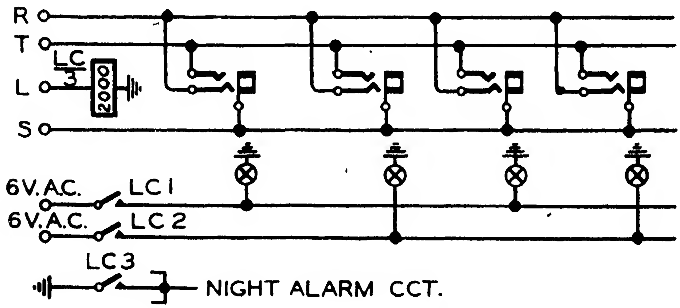


FIG. 250. MULTIPLE ANSWERING JACKS

ordinary 'click' test is still operative, and is used during slack periods when the F.L.S. power supply is cut off.

Fig. 249 shows the circuit arrangement. Relay *VC* operates when a circuit is taken into use, and contacts of this relay transfer the 6-volt a.c. supply to the next disengaged circuit. The 6-volt supply is obtained from the mains via a suitable step-down transformer. Several sets of lamps may be used,

each controlled by separate *VC* contacts, in cases where long cable runs to the switchboard would cause a voltage drop sufficient to prevent the lamps glowing fully. The number of lamp appearances per set must not exceed twenty-six, owing to limitations of conductor resistance and current carrying capacity.

Answering Multiple. Each answering jack and lamp is multipled every four, six, or twelve panels according to traffic requirements. The lamps and jacks are connected throughout in parallel, but the lamps are wired in sets of ten on each feed, the various feeds being commoned on the lamp side of the *LC* (lamp relay) contacts. 6-volt a.c. is used to supply the lamps, and the circuit is shown in Fig. 250. It will be noted that one side of the lamp is earthed at the switchboard.

CHAPTER XIII

TESTING

For the localization of faults in apparatus and overhead lines, it is usual to make resistance tests, the results of which can be used to give an indication of the location and type of fault. The simplest test is for a disconnection, in which case the faulty line is earthed at various consecutive points between the testing and distant ends, until the voltmeter gives a deflection. The fault is then known to exist in the section between the last two points earthed.

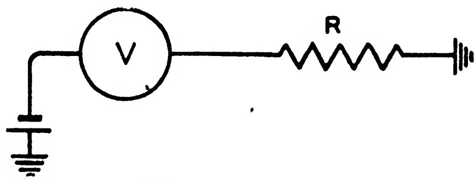


Fig. 251. Measurement of Resistance by Voltmeter

If an earth fault is being located, the procedure is reversed, and the line is disconnected at consecutive points until the deflection ceases.

Such a test is usually made from a test desk by the test clerk with equipment described later.

Voltmeter Tests. Loop and insulation resistance measurements may be made by means of a voltmeter and battery.

To measure the value of the resistance R_x (Fig. 251), the testing battery voltage is chosen so that direct application of the battery across the voltmeter terminals results in a full scale, or nearly full scale, deflection of the voltmeter. 80 volts and 8 volts are the values usually employed in exchange testing, the voltmeter having two suitable scales. Let the direct voltage reading be V_1 volts. The resistance R_x to be tested is then connected in series with the battery and voltmeter, the circuit being completed via the earth connection, or via a suitable return circuit to the positive terminal of the battery. If the resistance of the return (earth or other conductor) is not negligible compared with R, it must first be determined separately by the same method.

The deflection of the voltmeter with R_x in series is then noted. Call this V_2.

Then if R_v is the resistance of the voltmeter, it follows that the total current in the circuit is $V_1/(R_v + R_x)$. This produces a potential drop of V_2 volts across the voltmeter, i.e. across the resistance R_v, and the potential difference, $V_1 - V_2$, is lost in R_x. But the same current flows in R_v and R_x, and their

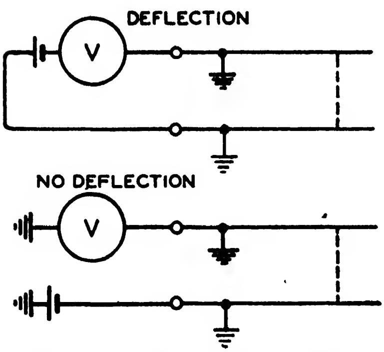


FIG. 252. TESTING FOR CONTACT

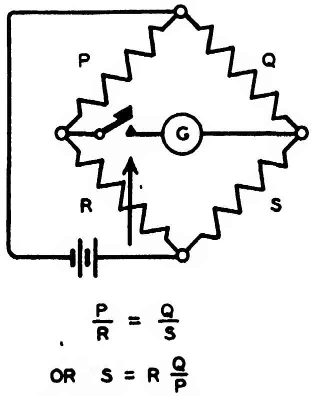


FIG. 253. WHEATSTONE BRIDGE

resistances are therefore proportional to the voltages across them.

Therefore $$R_v/R_x = V_2/(V_1 - V_2)$$
and $$R_x = R_v \,.\, (V_1 - V_2)/V_2$$

The most accurate results are obtained when R_x is approximately equal to R_v, and the voltmeter scale must be suitably changed, by means of the shunt key provided, to obtain an approximation to this condition.

Schedules are provided to test clerks showing the resistances corresponding to given voltmeter readings when known testing voltages are applied.

When contact is suspected between two wires, the precaution must be taken to earth the voltmeter and apply it to one of the faulty lines, whilst earthed battery is applied to the other. The diagram shows that if the voltmeter is not earthed, an earth fault on each circuit might be interpreted as a contact. (Fig. 252.) As the exchange testing battery is normally earthed, this precaution is automatically taken by the test clerk (see test cord circuit).

Wheatstone Bridge. If the loop or insulation resistance of a circuit or piece of apparatus is required, the Wheatstone bridge principle may be employed. Fig. 253 shows the connections. The resistance to be measured is referred to as S, the rheostat as R, and the ratio arms as P and Q. The Post Office pattern of this box has resistance values which allow R to be varied from 1 to 11 110 ohms, and P and Q to be either 10, 100 or 1 000 ohms each.

With the bridge connected as shown, the value of R is changed until the deflection on the meter is zero, or a minimum value, when the battery key is depressed. The potential drop across P must then be the same as across Q, and the drop is therefore also equal across R and S.

As negligible current is flowing in the meter, it follows that—

$$(\text{current in } P) \times (\text{resistance } P) = (\text{current in } Q) \times (\text{resistance } Q)$$

and

$$(\text{current in } R) \times (\text{resistance } R) = (\text{current in } S) \times (\text{resistance } S).$$

Dividing the first equation by the second, and simplifying, the well-known result $P/R = Q/S$ is obtained. It is also true that $P/Q = R/S$ and either form leads to $S = R \,.\, Q/P$.

Now if Q and P are equal, S is equal to R, whilst by making the ratio Q/P equal to 0·01, 0·1, 10 or 100, values of S from 0·01 ohms to 1 111 000 ohms may be obtained. A high voltage and sensitive meter are required when testing resistances approaching a megohm, and conversely low voltage and a low resistance meter must be used for testing values of less than a few ohms.

Megger. A more convenient instrument than the Wheatstone bridge is the megger. Two forms are in general use, a 500-volt instrument for testing insulation resistances from 100 000 ohms to 100 MΩ, and a 250-volt instrument measuring up to 20 MΩ. The latter may be adapted for bridge work by the operation of a switch incorporated in the instrument. The switch connects the two halves (125 volts each) of the generator windings in parallel, and places the current coil across a bridge network of resistances contained in the instrument case.

By the addition of an external rheostat the bridge is completed, and resistances from 0·01 times the lowest to 100 times the highest value of the rheostat may be measured, suitable use

being made of the ratio switch, which taps a resistor at three points to obtain ratios of 1 to 1, 1 to 10, and 1 to 100. Interchanging the line and rheostat connections allows the inverse of these ratios to be effective.

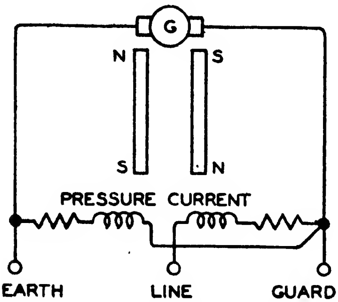


FIG. 254A. MEGGER CONNECTIONS

In the megger proper, the d.c. generator of 250 or 500 volts consists of armatures rotating between the poles of two permanent magnets, the other ends of which are used to provide a field for the moving coil system. The voltage is produced by rotating the armatures at high speed, either by a geared-up handle or by a small electric motor, a slipping clutch maintaining the voltage constant when the critical speed is exceeded. The megger owes its sensitivity to the fact

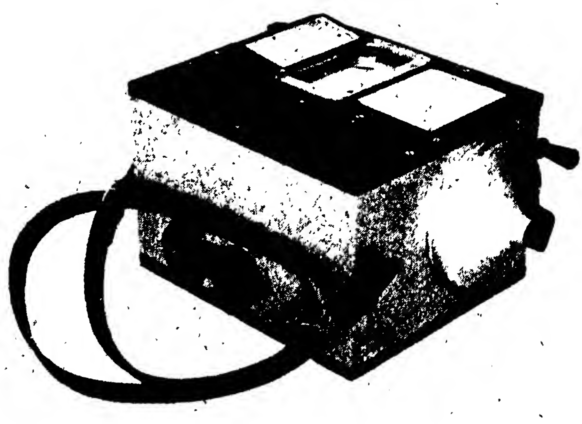


FIG. 254B. MEGGER
(*Evershed & Vignoles, Ltd.*)

that no return spring is used on the moving or 'current' coil; a second or 'pressure' coil, connected across the generator, and in series with a resistance, produces the restraining force, and normally keeps the needle on the 'infinity' mark when the external circuit is disconnected. A high resistance is connected

in series with the line terminal to avoid damaging the instrument by external short circuits, and to reduce the difference between the current strengths when measuring high and low extremes of resistance. A special megger, indicating up to 2 000 MΩ, is sometimes used for measuring the insulation resistance of cables. An important feature in such measurements is the use of the guard wire, to prevent false readings owing to

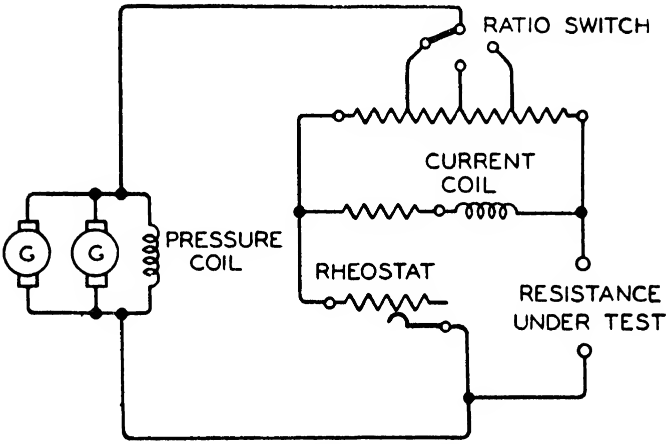


FIG. 255. BRIDGE MEGGER CONNECTIONS

current flow across the surface of the exposed insulator when the conductor is bared for test. An additional terminal, connected internally to the high voltage side of the megger generator, is used to connect a wire to the exposed insulation at the end of the cable under test, and the bared end of the wire is usually wrapped completely round the insulation an inch or so from where it enters the cable sheath. When the megger is excited, any current flow to the sheath over the surface of the insulation comes from the guard wire, and does not therefore pass through the current coil which carries only the current which leaks through the insulation, and registers the corresponding resistance (Fig. 256).

When testing circuits containing inductance or capacitance, great care must be taken to maintain the megger voltage constant, and to apply it to the line or apparatus under test for a sufficiently long period to ensure that steady-state conditions have been reached.

Special Tests. Ordinary loop or insulation resistances may be determined by the methods set out above. Where the exact location of an earth or contact fault on a line is required, however, a modified method of testing must be adopted. The Varley and Murray tests are those usually adopted to estimate the location of an earth fault on a line. Fig. 257 shows the connections for the Varley test. The loop resistance of the

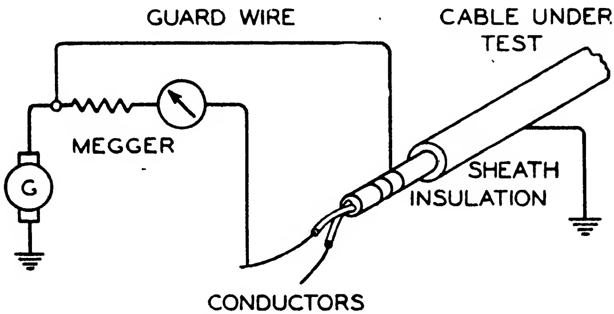


FIG. 256. USE OF GUARD WIRE

faulty pair is first measured by an ordinary application of the Wheatstone bridge. The connections are then changed to those shown, and the rheostat varied until balance is obtained. If L ohms is the total resistance of the loop conductor, and X ohms the resistance to the fault from the testing end, the balance of the bridge is obtained when

$$\frac{P}{Q} = \frac{R + X}{L - X}$$

and if $P = Q$, as can usually be arranged,

then $$R + X = L - X$$

or $$X = \tfrac{1}{2}(L - R).$$

The conductor resistance in ohms per mile will be known, and the distance of the fault may be obtained by direct proportion. If the resistance of the circuit is not constant throughout, allowance must be made for the changes, and the above formula will still be true since L and X are the resistances of the particular components of the circuit. It will be noted that the actual resistance of the earth fault is immaterial, since it occurs only in the battery circuit.

The test is not accurate if the insulation resistance of the conductors is low, or if the earth fault is not located at one point, e.g. where a low insulation fault exists over a length of cable.

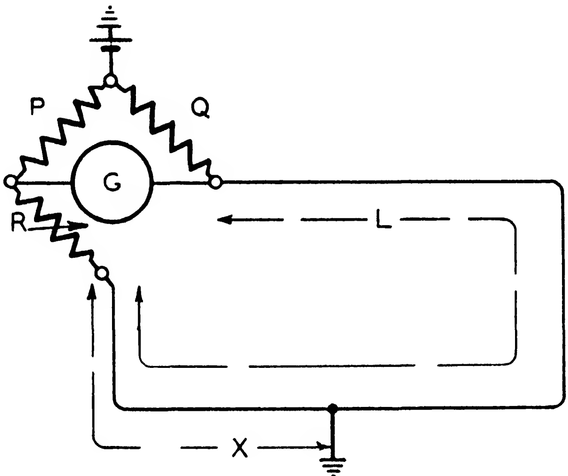


FIG. 257. VARLEY TEST

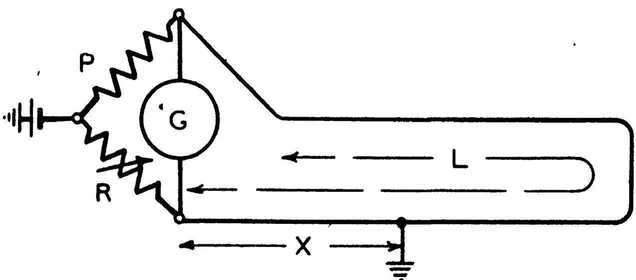


FIG. 258. MURRAY TEST

The Murray test is somewhat similar, and the connections are given in Fig. 258.

The bridge is balanced when

$$P/(L - X) = R/X,$$

or

$$PX = RL - RX$$

or

$$X = RL/(P + R).$$

The loop resistance L is first found, as in the Varley test, and the distance of the fault is similarly calculated from the known constants of the particular circuit.

Test Desk. The exchange testing equipment is centralized on a test desk, or in small exchanges, on a test panel. In trunk exchanges and repeater stations, test racks are used, the relay apparatus being mounted above the test positions on an iron

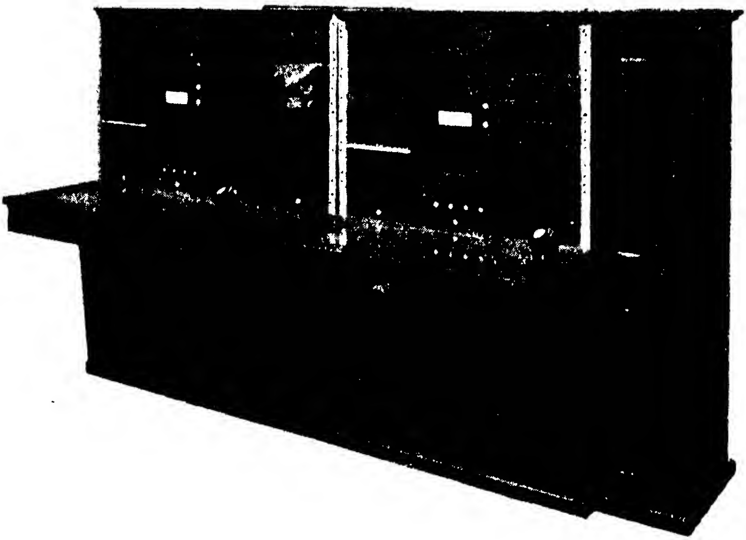


FIG. 259. TEST DESK
(*General Electric Co. Ltd.*)

framework. In all types, the fundamental testing circuits are similar.

Illustrations of different types of Test position are given in Figs. 259 and 261, test racks in Fig. 260. In general, the test clerks, one per position, are provided with headgear receivers and breastplate transmitters, connected to the position speaking circuit by means of a flexible cord and four-way plug, as on an operator's position.

Incoming and outgoing lines to and from the exchange terminate on lamp signalling calling equipments in front of the test clerks, so that operators or subscribers may obtain direct access to the testing positions.

In automatic exchanges, jacks giving access to test distributors, thence to test final selectors, are provided; and over

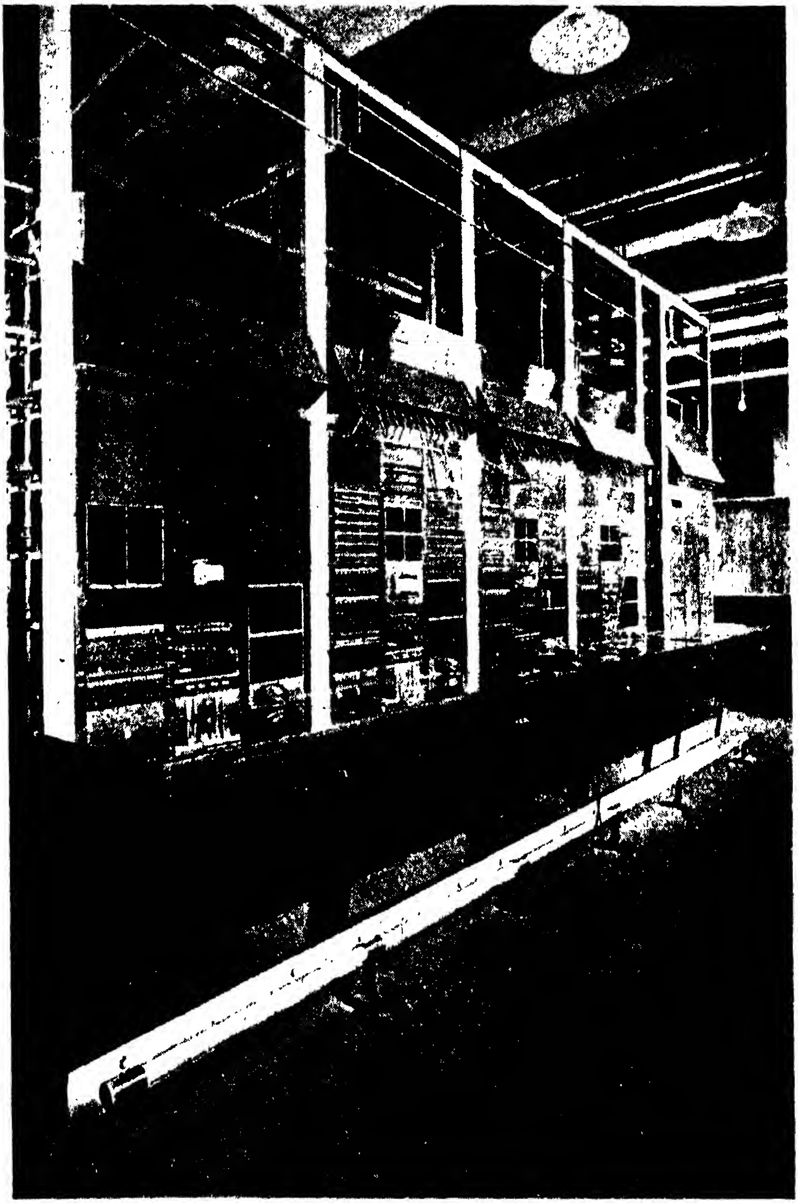


FIG. 260. TEST RACKS
(*Siemens Bros. & Co. Ltd.*)

these circuits the test clerk may obtain connection, by dialling, to any subscriber's line on the exchange. Test wires, in addition to control wires, are employed, so that the tests are conducted via the selector train without interfering with the switch stepping circuits.

In manual exchanges, the same facility is provided by means

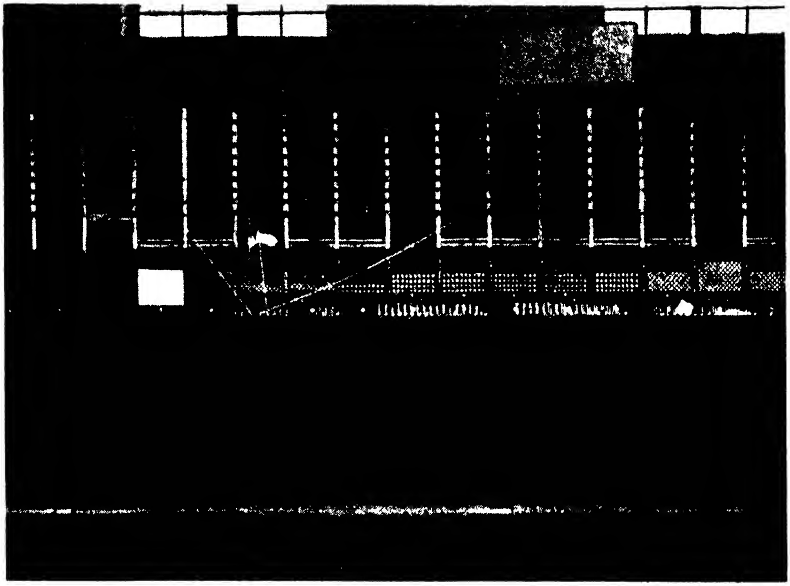


FIG. 261. TEST POSITION, MANUAL EXCHANGE
(*Siemens Bros. & Co. Ltd.*)

of direct lines to the switchboard, at which they terminate on the exchange testing position (where such is provided), located at the end of the A-suite. From this point the operator on the switchboard extends the test desk circuit by means of a plug and cord to any multiple line, and testing may proceed over the ordinary multiple connection. Most of the testing is conducted via the test cord circuit, a simplified diagram of which is given in Fig. 262.

The test battery and voltmeter may be applied to the line in many ways, depending on the particular test it is desired to make. The usual test for a subscriber's line is to obtain connection via the multiple (utilizing the test distributor or extension line to manual board) and then throw the VOLTMETER

and EARTHING keys. This applies battery to the B-line via the voltmeter, and will show up an earth fault by a deflection on the meter. (The exchange calling equipment is removed from the line by operation of the cut-off relay.) This being satisfactory, the reversing key is operated quickly, and the battery is now applied to the A-line, and earth to the B.

If the subscriber's line and instrument are satisfactory, the voltmeter needle will swing over the scale, and return to zero, indicating the discharge, and subsequent charge in the reverse direction of the condenser in the subscriber's telephone. The magnitude of the swing gives an indication of the isulation resistance of the line. A permanent deflection indicates that the A-line is earthing.

The receipt of a current on either line may be verified by the operation of the VOLTMETER, and RECEIVE NEGATIVE keys, with the addition of the REVERSING key as required. The low voltage scale can be used when measuring low values of loop resistance or earth faults. A complete card index of all subscribers' and junction lines is accessible to the test clerk, and on these cards the constants and composition of the circuits are recorded, as well as details of faults which have occurred since the circuit was first connected.

In addition to access via the multiple, direct connection to the subscriber's line may be obtained. The test desk is situated as near as possible to the M.D.F., and jacks on the former are wired to jacks on the top of the latter. By removal of the line fuses the test clerk can obtain direct access to the external cable, a special plug connected to a flexible cord being inserted in the line fuse clips, and a switchboard plug at the other end of the cord being inserted in a jack connected to the test desk.

Alternatively, on the exchange side of the M.D.F., a horseshoe shaped test plug can be inserted into the protector fitted to each line. By this means the internal and external circuits are separated, and are joined through to the test clerk by the same means as described above.

The connections of an interception circuit providing these features, together with the facility of observing the progress of a call without interference, is shown in Fig. 263. Whilst one side of the circuit is being tested, a call received from the other side actuates the supervisory signal and warns the test clerk.

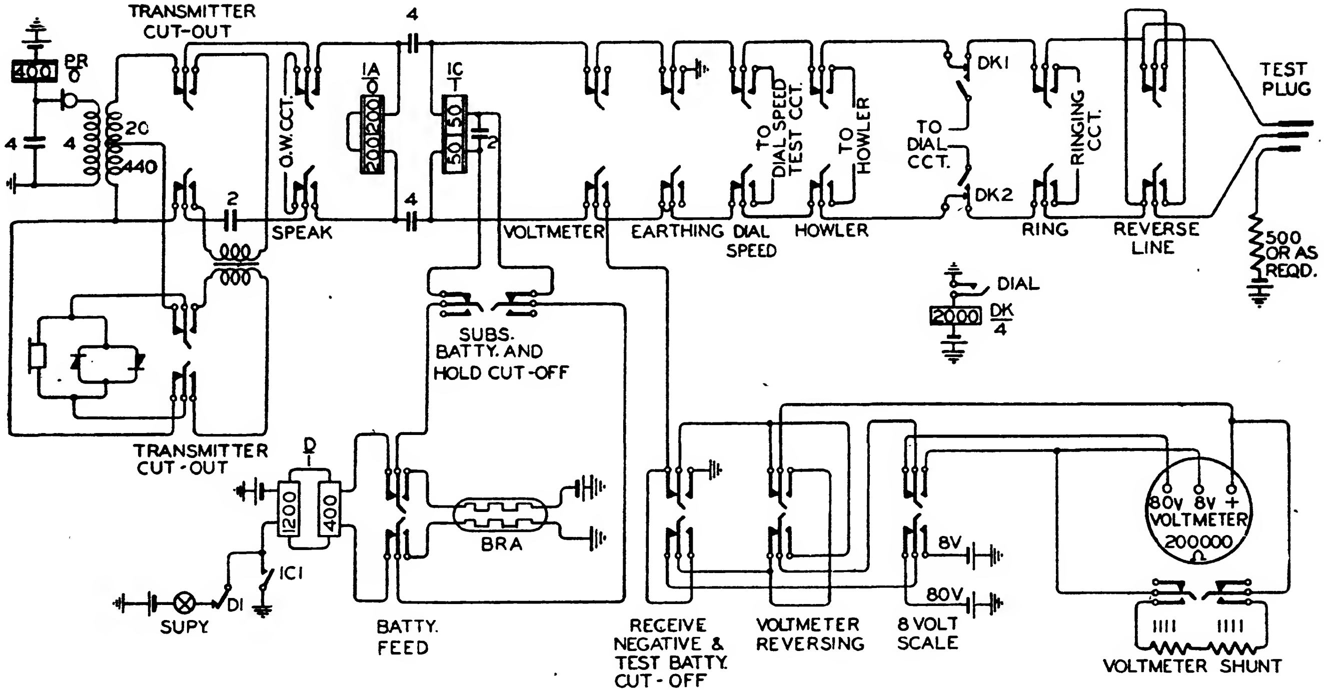


FIG. 262. TEST CORD CIRCUIT

Exchange Test Position. In C.B. manual exchanges where test positions are provided at the end of the A-suite, operators at these positions are given certain testing facilities, to verify the faults reported to the monitors.

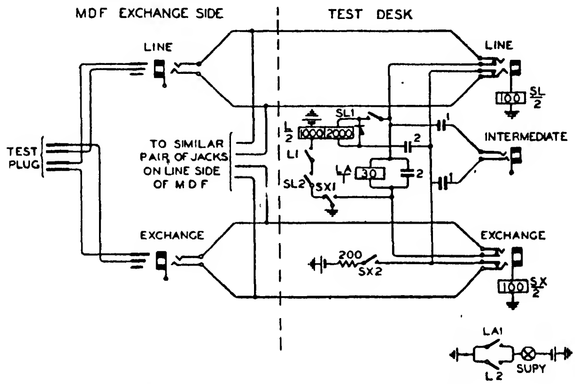


Fig. 263. Test Interception Circuit

A voltmeter is provided, and a test cord circuit which is a simplification of that on the test desk. When the nature of the fault has been verified, the fault docket is dispatched to the

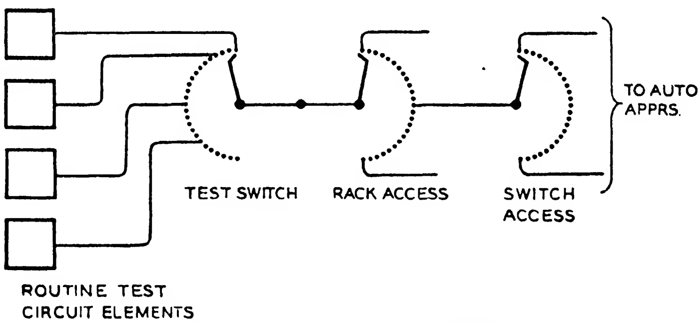


Fig. 264. Routiner Schematic

test clerk by pneumatic tube, so that a detailed investigation may be made. The test positions are fitted at the end of the A-suite so that any test made by the operators, or by the test clerk on an extension circuit to the manual board, shall be conducted over the greater part of the subscribers' multiple.

Routine Testing. The apparatus most frequently used in manual and automatic exchanges, such as cord circuits and

selectors, is regularly routine tested by special test sets. The design of these sets is beyond the scope of this work, but the principle is that every facility afforded by the circuit under test is checked by the tester under conditions slightly worse than will be met in service. If the apparatus fails to respond, an alarm is given, and the testing officer traces and remedies the fault. Calling equipments are checked over loops of the maximum permissible resistance, cord circuit supervisory relays similarly, with line leakage allowed for, and automatic switches are impulsed over lines of maximum conductor resistance or minimum insulation resistance, with impulses distorted to the maximum limits allowed, and at extreme battery voltages. In the manual case, the tests are carried out by hand, but in automatic exchanges the tests are largely self-conducted by automatic routiners. Access switches are provided to connect the routiners to individual apparatus items, and a schematic arrangement is shown in Fig. 264.

CHAPTER XIV

TELEPHONE TRANSMISSION THEORY

Sound Waves. The primary sensation known as *sound* is caused by vibrations in the air acting upon the external ear; they are passed on to the inner ear which is the wonderful mechanism giving the sense of hearing. The vibrations are propagated through the air as a wave motion in a somewhat similar way to that of waves on the surface of a pond. Their speed of travel through the air at ordinary temperatures is about 1 100 ft. per sec. These sound waves are produced in the first instance by the mechanical vibration of some object such as a piano string, or by a resonating column of air as in an organ pipe.

Sound has three qualities, *pitch*, *intensity*, and *timbre*. The pitch of a note is the number of vibrations per second in the principal or fundamental frequency, or in music the position of the note in the musical scale relative to middle 'C' which has a frequency of 256 vibrations per sec. Doubling the frequency of a note raises it one octave, and conversely halving the frequency lowers the note one octave. The average human ear can respond to frequencies from about 20 per sec. to about 16 000 or 20 000 per sec. The intensity of a sound is the power conveyed by the waves. It is frequently referred to as 'loudness' but the apparent loudness of a sound of a given intensity depends upon the various frequencies composing the sound. The ear is most sensitive to frequencies round about 2 000 per sec. The timbre of a sound might be described as its quality or pleasing effect, and it depends on the mixture of frequencies composing the sound. A musical sound consists of a principal or fundamental frequency with the addition in various proportions of other frequencies which are multiples of the fundamental. These multiple frequencies are known as *harmonics*: the one with twice the frequency of the fundamental is known as the *second harmonic*: the one with three times the frequency is the *third harmonic*, and so on. The characteristic sounds of the various musical instruments are due to the different ratios of harmonics that they contain. In the

miscellaneous sounds classed as noise the component frequencies are not definitely related to one another.

Speech Waves. The sounds of speech are produced by the vocal cords and the resonating cavities of the throat, nose and mouth. The waves produced are a complicated mixture of frequencies: an idea of the complexity can be obtained from Fig. 265 giving the wave forms for a number of vowel sounds

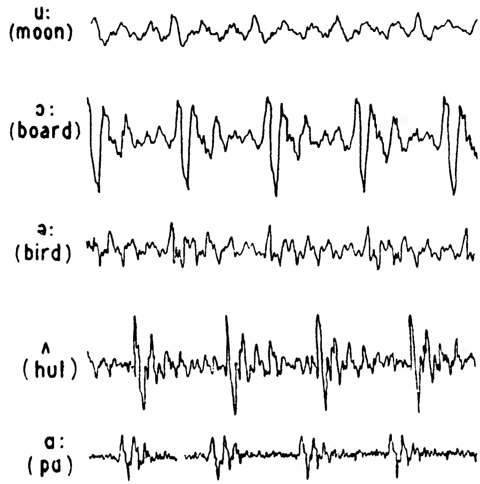


FIG. 265. WAVE FORMS OF STANDARD VOWELS

It has been found by experiment that each of the vowel sounds consist essentially of either two or three fundamental frequencies between 100 and 2 500 per sec., but mostly between 350 and 1 200 per sec. These fundamental frequencies are of appreciable duration and are definitely periodic. The consonants are essentially ways of starting and stopping the vowel sounds, and are thus of a transient nature, i.e. they are not periodic and have very complicated wave forms. The frequencies comprising them range from about 150 per sec. to many thousands.

A telephone transmitter can be regarded as an artificial ear, and it is shown in Chapter II how it acts as an alternator producing alternating currents of the same frequency as the sound waves causing the diaphragm to vibrate.

Most of the energy in speech waves is carried by the frequencies between 500 and 1 700 per sec., and a telephone circuit

which transmitted only these frequencies would give fairly intelligible speech but difficulty would be experienced with some of the vowel sounds and many of the consonants such as p, b, f, s, z, etc. If the frequency band were extended to include all components between 200 and 3 000 per sec. the 'naturalness' of the reproduced speech would be very greatly improved, and very little difficulty would be experienced in discriminating between similar consonants. In ordinary conversation, however, the meaning of the words assists greatly in the interpretation of the received sound, and good commercial speech can be obtained with a frequency band of 250 to 2 400 per sec. With modern equipment and cables the frequency band of commercial circuits is increasing, and the C.C.I.F.* has recommended (1934) that 2 600 should be the higher limit. The question of high frequency cut-off is dealt with again in Chapter XV. The advent of broadcasting with its wider frequency band and consequent higher quality reproduction, has made the telephone public more critical of the quality of reproduction obtained from commercial telephones.

Mean Speech Frequency. In telephone transmission problems it is very convenient to be able to use a single frequency for the purposes of measurement and calculation, which will give approximately the same results as actual speech tests. Telephone circuits cut off the very low frequencies and the high frequencies, but have an attenuation-frequency characteristic which is sensibly a constant over the range of frequencies which conveys most of the energy of sound waves, i.e. 500 to 1 700 per sec. A frequency of 800 cycles per sec., which is roughly an intermediate frequency, has been found suitable and termed the *mean speech frequency*. The term is, however, misleading, for all that is necessary—provided that the circuit has an effective frequency band sufficient to give good articulation—is to choose some frequency in that part of the frequency band over which the attenuation is reasonably constant.

In transmission calculations the angular velocity in radians per second is required. It is termed the *pulsatance*, denoted by ω, and is equal to 2π times the frequency. A value of $\omega = 5\ 000$, equivalent to 796 per sec. is taken for the mean speech frequency.

* Comité Consultatif International Téléphonique.

Line Equations (Steady-state). Consider what happens to these speech currents from a telephone transmitter when they are applied to telephone lines. It is known, of course, that unless some amplifying device is introduced, they become weaker as they progress along the line; in fact in a normal telephone call, by far the greater part of the power from the transmitter is used up in the line, and only the remaining fraction is delivered to the distant receiver.

Consider a line having uniformly distributed primary constants, that is, series constants of R ohms and L henries per mile, and shunt constants of G mhos and C farads per mile. G is of course the reciprocal of the insulation resistance per mile.

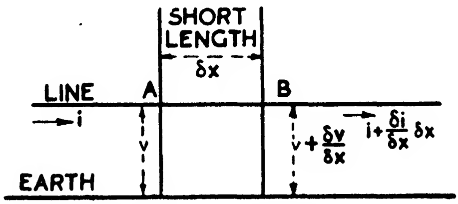


FIG. 266. ELEMENT OF TRANSMISSION LINE

Take a short length of the line δx as shown in Fig. 266. This short length of line between the points A and B will have the following electrical values—

$\delta x\, R$ ohms, resistance

$\delta x\, L$ henries, inductance,

$\delta x\, G$ mhos, leakance,

$\delta x\, C$ farads, capacitance;

the voltage will decrease along the length of the line at the rate dv/dx and the voltage drop between A and B will be $(dv/dx)\delta x$ if δx is small. Then—

Voltage drop = resistance drop + reactance drop.

or $$-(dv/dx)\delta x = iR\delta x + (di/dt)L\delta x,$$

the negative sign showing the decrease in voltage. In this voltage equation i can be regarded as a constant for the short length δx; therefore—

$$-(dv/dx) = Ri + L(di/dt) \quad . \quad . \quad . \quad (1)$$

Similarly the current is decreasing along the line at a rate di/dx and the change between A and B will be $(di/dx)\delta x$. Then

$$\text{Current loss} = \text{leakance loss} + \text{capacitance loss},$$

or
$$-(di/dx)\delta x = vG\delta x + (dv/dt)C\delta x;$$

and again, since δx is small, v can be regarded as a constant in this current equation and—

$$-(di/dx) = Gv + C\,.\,dv/dt \quad . \quad . \quad . \quad (2)$$

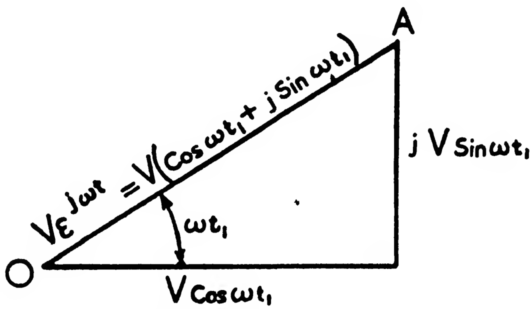


FIG. 267. VECTOR QUANTITIES

In the solution of the above equations the first step is to get rid of di/dt and dv/dt.

If the applied voltage is a simple sine wave with an angular velocity of ω radians per sec., ($\omega = 2\pi f$).

$$v = V\varepsilon^{j\omega t}$$
$$i = I\varepsilon^{j\omega t}$$

where V and I are peak values. Here for mathematical convenience vector operators have been used, of the form $\varepsilon^{j\theta}$, which rotates a vector through θ radians without affecting its magnitude. By de Moivre's theorem—

$$\varepsilon^{j\theta} = \cos\theta + j\sin\theta$$

and
$$\varepsilon^{-j\theta} = \cos\theta - j\sin\theta,$$

which gives another way of writing the vector operator and affords a clearer idea of the process. The voltage vector is shown in Fig. 267 for a time t_1.

The vector OA is of course rotating at ω radians per sec. anticlockwise.

From the vector equations for voltage and current,

$$dv/dt = j\omega V\varepsilon^{j\omega t} = j\omega v.$$
$$di/dt = j\omega I\varepsilon^{j\omega t} = j\omega i.$$

Equations (1) and (2) now become—

$$-(dv/dx) = Ri + j\omega Li = i(R + j\omega L) \quad . \quad (3)$$
$$-(di/dx) = Gv + j\omega Cv = v(G + j\omega C) \quad . \quad (4)$$

i can be eliminated from the voltage equation, and v from the current equation, by differentiating (3) and (4) again.

$$d^2v/dx^2 = (R + j\omega L)(G + j\omega C)v,$$
$$d^2i/dx^2 = (R + j\omega L)(G + j\omega C)i.$$

The product of the two brackets in these equations is a constant for any particular value of ω and it is usually denoted by P^2.

Then $$P = \sqrt{[(R + j\omega L)(G + j\omega C)]} \quad . \quad . \quad (5)$$

and $$d^2v/dx^2 = P^2v, \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$
$$d^2i/dx^2 = P^2i \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Differential equations have now been obtained for the voltage and current along a uniform line, the solutions of which will not be developed here but will simply be stated as follows. They can be verified by differentiating.

$$v = A\varepsilon^{-Px} + B\varepsilon^{Px}. \quad . \quad . \quad . \quad (8)$$
$$i = C\varepsilon^{-Px} + D\varepsilon^{Px}. \quad . \quad . \quad . \quad (9)$$

Thus the voltage v at a point x along the line is expressed by two factors: one, $A\varepsilon^{-Px}$, which decreases logarithmically according to ε^{-Px}, and a second, $B\varepsilon^{Px}$, which increases towards the distant end according to ε^{Px}. The first of these is the incident wave and the second is a reflected wave. The factors, A, B, C, and D depend upon the terminal conditions of the line at the sending and receiving ends. The constant P controls the rate of logarithmic increase and decrease and is known as the Propagation Constant. Fig. 268 shows the two logarithmic curves.

The factors A, B, C, and D will now be evaluated for certain special cases.

The Infinite Line. Considering the case of a uniform line which is infinitely long it will be evident that at a point extremely far distant along this line the voltage and current will become zero or at any rate infinitely small. Substituting $x = \infty$, $v = 0$, and $i = 0$, in equations (8) and (9), the result is

$$0 = A\varepsilon^{-P\infty} + B\varepsilon^{P\infty}$$
$$0 = C\varepsilon^{-P\infty} + D\varepsilon^{P\infty}.$$

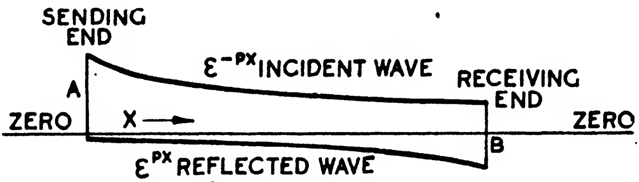


FIG. 268. REFLECTED AND INCIDENT WAVES

These equations can only be true if B and D are zero; therefore

$$v = A\varepsilon^{-Px},$$
$$i = C\varepsilon^{-Px}.$$

Now at the point $x = 0$ the voltage v is the sending end voltage; call this v_s.

Then $\quad v_s = A\varepsilon^{-Po}$ or $v_s = A$.

$$\therefore \quad v_x = v_s\varepsilon^{-Px} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

Similarly

$$i_x = i_s\varepsilon^{-Px} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

These are the equations for voltage and current along an infinite line, and they are of great importance in the study of transmission problems.

It will be seen from (10) and (11) that the ratio voltage/current is constant throughout the length of the line, and such a constant is of course in the nature of an impedance; in this case it is termed the *characteristic impedance*, and designated by Z_o. This can be found in terms of the primary constants as follows.

Differentiating (10); $dv_x/dx = -Pv_s\varepsilon^{-Px} = -Pv_x$, and from equation (3); $-(dv_x/dx) = i_x(R + j\omega L)$.

$$i_x(R + j\omega L) = Pv_x = \sqrt{[(R + j\omega L)(G + j\omega C)]}\, v_x$$

$$\therefore \quad \frac{v_x}{i_x} = Z_o = \sqrt{\left[\frac{R + j\omega L}{G + j\omega C}\right]} \quad . \quad . \quad . \quad (12)$$

Z_o can be described as the impedance of an infinitely long line, or as the relation of voltage to current on a line without reflection effects. The idea of an infinite line is extremely useful in the study of transmission problems as it allows one to arrive at formulae which are very much simplified, and at the same time it does not take one far from practical conditions.

It will later be shown how a line which has a value for Px approaching 2 can be regarded as an infinite line, and also that much shorter lines can be made equivalent to infinite lines by terminating them with an impedance equal to their characteristic impedance Z_o.

Finite Line (General Case). The constants A, B, C, and D in equations (8) and (9) can be determined for a finite line as follows.

Differentiating (8)—

$$dv/dx = P\,(-A\varepsilon^{-Px} + B\varepsilon^{Px}),$$

and from (3)—

$$-(dv/dx) = i(R + j\omega L)$$

$$\therefore\ -[i(R + j\omega L)/P] = -A\varepsilon^{-Px} + B\varepsilon^{Px} = -iZ_o.$$

When $x = 0,\ i = i_s =$ sending current,

and $v = v_s =$ sending voltage.

Then $i_sZ_o = A - B$

and $v_s = A + B.$

$$\therefore\ A = \tfrac{1}{2}(v_s + i_sZ_o), \qquad B = \tfrac{1}{2}(v_s - i_sZ_o),$$

$$C = \tfrac{1}{2}(i_s + v_s/Z_o), \qquad D = \tfrac{1}{2}(i_s - v_s/Z_o).$$

Substituting these values in (8) and (9),

$$v_x = \tfrac{1}{2}(v_s + i_sZ_o)\,.\,\varepsilon^{-Px} + \tfrac{1}{2}\,(v_s - i_sZ_o)\,.\,\varepsilon^{Px}.$$

$$i_x = \tfrac{1}{2}(i_s + v_s/Z_o)\,.\,\varepsilon^{-Px} + \tfrac{1}{2}\,(i_s - v_s/Z_o)\,.\,\varepsilon^{Px}.$$

It is convenient at this stage to change these equations from the exponential form to the hyperbolic form. Write θ for Px termed the *attenuation length*. Then since

$$\sinh\theta = \tfrac{1}{2}(\varepsilon^{\theta} - \varepsilon^{-\theta}),\ \cosh\theta = \tfrac{1}{2}(\varepsilon^{\theta} + \varepsilon^{-\theta}),$$

$$\tanh\theta = (\varepsilon^{\theta} - \varepsilon^{-\theta})/(\varepsilon^{\theta} + \varepsilon^{-\theta}),\ \coth\theta = (\varepsilon^{\theta} + \varepsilon^{-\theta})/(\varepsilon^{\theta} - \varepsilon^{-\theta}$$

$$\underline{\underline{v_x = v_s\cosh\theta - i_sZ_o\sinh\theta}} \qquad (13)$$

$$\underline{\underline{i_x = i_s\cosh\theta - (v_s/Z_o)\sinh\theta}} \qquad (14)$$

These equations express the voltage and current along any uniform line in terms of the sending end values v_s and i_s.

Despite the apparent difficulty of hyperbolic functions they greatly simplify the solution of transmission problems, and their use should be accepted at this stage. They are related to the hyperbola in somewhat the same way as trigonometrical functions are related to the circle, but the telephone engineer need not consider their geometrical significance. Only simple operations with these functions are required, which can always be proved by substituting the exponential equivalents given above. Their advantage lies in the fact that by using them all the functions of ε^{θ} and $\varepsilon^{-\theta}$ take care of themselves, i.e. all reflection effects are automatically taken into account. A full demonstration of this will be found on p. 352. Fig. 269 shows values of sinh θ, cosh θ, tanh θ, and coth θ for values of θ between 0 and 4. The exponential functions ε^{θ} and $\varepsilon^{-\theta}$ are also shown.

From the general equations (13) and (14) expressions will now be developed for the sending end impedance of a finite line.

Sending End Impedance with Receiving End Short-circuited (Z_{sc}). In this case the voltage at the distant end of the line will obviously be zero.

Then from (13) $\quad 0 = v_s \cosh \theta - i_s Z_0 \sinh \theta.$

or $\quad v_s/i_s = Z_0 \tanh \theta.$

Now v_s/i_s is the sending end impedance Z_{sc}.

$$\therefore \quad Z_{sc} = Z_0 \tanh \theta \qquad . \quad . \quad . \quad (15)$$

Sending End Impedance with Receiving End Open-circuited (Z_{so}). In this case the current at the distant end will be zero; therefore, from (14)

$$0 = i_s \cosh \theta - (v_s/Z_0) \sinh \theta.$$

or $$v_s/i_s = Z_{so} = Z_0 \coth \theta \qquad . \quad . \quad . \quad (16)$$

The Practical Value of Equations (15) and (16). Rearranging formulae (15) and (16);

$$Z_0 = Z_{sc} \coth \theta.$$

$$Z_0 = Z_{so} \tanh \theta.$$

Multiplying together;

$$Z_0^2 = Z_{sc} Z_{so},$$

or $$Z_0 = \sqrt{(Z_{sc} Z_{so})} \qquad . \quad . \quad . \quad (17)$$

Expressed in words this means that the characteristic impedance is equal to the geometric mean (square root of the product) of the two sending end impedances taken with the

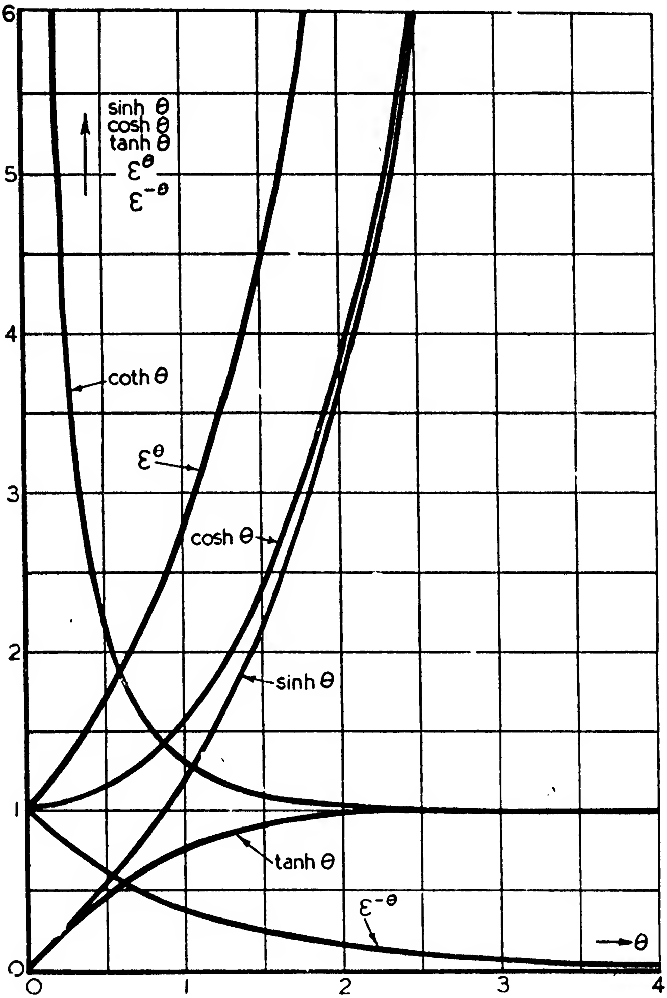


FIG. 269. HYPERBOLIC AND EXPONENTIAL FUNCTIONS

receiving end opened and closed respectively. This gives an easy method of finding the characteristic impedance of any line simply by finding two sending end impedances.

Sending End Impedance of a Line Terminated with an Impedance Z. If the line be terminated at the point x the voltage at this point will be $i_x Z$;
therefore from (13)

$$i_x Z = v_s \cosh \theta - i_s Z_o \sinh \theta \qquad (a)$$

and (14) gives

$$i_x = i_s \cosh \theta - (v_s/Z_o) \sinh \theta \qquad (b)$$

substituting (b) in (a)

$$\frac{v_s}{i_s} = Z_s = Z_o \left\{ \frac{Z \cosh \theta + Z_o \sinh \theta}{Z_o \cosh \theta + Z \sinh \theta} \right\} \qquad (18)$$

This can also be written in an exponential form if desired;

$$Z_s = Z_o \frac{1 + \varepsilon^{-2\theta}\left(\dfrac{Z - Z_o}{Z + Z_o}\right)}{1 + \varepsilon^{-2\theta}\left(\dfrac{Z_o - Z}{Z_o + Z}\right)} \qquad (18a)$$

Characteristically Terminated Line. It will be seen from (18) that if Z is made equal to Z_o, then the quantity in the bracket reduces to unity and Z_s equals Z_o. This means then that a line acts as an infinite line if terminated with its characteristic impedance, and there will be no reflection effects. This fact is of very great importance in the design of telephone apparatus.

Equations (13) and (14) will solve all uniform line problems, but in practice only terminal effects are required, which can often be calculated more readily from the artificial line formulæ which will be given later.

Transmission as a Wave Motion. In the preceding sections expressions have been obtained for voltage and current and impedance which are all dependent upon the two derived secondary constants, propagation constant P and characteristic impedance Z_o.

$$P = \sqrt{(ZA)} \text{ and } Z_o = \sqrt{(Z/A)},$$

where $Z = (R + j\omega L)$ is the series impedance,

and $A = (G + j\omega C)$ is the shunt admittance.

Both P and Z_o are complex, i.e. they have both real and unreal parts. In the case of Z_o the real part is the resistance and the unreal part is the reactance, as in ordinary a.c. theory. In the case of P the significance of the real and unreal parts is not so obvious, and they will now be dealt with fully.

The real part of P is known as the *attenuation constant*, denoted by β and the unreal part is known as the *wavelength constant*, denoted by α;

$$P = \beta + j\alpha.$$

The voltage and current along an infinite line are given by equations (10) and (11) where x is the distance from the sending end of the line.

$$v_x = v_s \varepsilon^{-Px}$$

$$i_x = i_s \varepsilon^{-Px}.$$

These can now be rewritten

$$v_x = v_s \, \varepsilon^{-\beta x} \varepsilon^{-j\alpha x} \quad . \quad . \quad . \quad (a)$$

$$i_x = i_s \varepsilon^{-\beta x} \varepsilon^{-j\alpha x} \quad . \quad . \quad . \quad (b)$$

In these equations $\varepsilon^{-j\alpha x}$ is of course a vector operator which rotates the vectors $v_s\varepsilon^{-\beta x}$ and $i_s\varepsilon^{-\beta x}$ through αx radians. This type of vector operator has already been described in a previous paragraph. Thus the complete expressions (a) and (b) mean that the voltage and current die away at the rate $\varepsilon^{-\beta x}$ and have a phase difference αx radians compared with the sending end current and voltage. It is important to remember that this phase shift is not an angular difference between the current and voltage. Any phase difference which does exist between the current and voltage depends upon the angle of Z_0, and is the same at all points along the line. This phase lag means that a time delay will occur before the changes in voltage and current impressed at the sending end are reproduced—to a reduced degree—at points along the line. This is the essential characteristic of a wave motion. If the applied voltage has a frequency of ω radians per sec., then αx radians will involve a time delay of t sec. where

$$t = \alpha x/\omega \quad . \quad . \quad . \quad . \quad (19)$$

The value of x when $t = 1$ will give the velocity S in miles per sec.

$$S = \omega/\alpha \quad . \quad . \quad . \quad . \quad (20)$$

The energy thus travels along the line as a wave motion with a finite velocity and with a frequency of f cycles per sec. ($f = \omega/2\pi$) the distance between successive voltage peaks will be the *wavelength* λ.

$$\lambda = 2\pi/\alpha \quad . \quad . \quad . \quad . \quad (21)$$

The propagation of a wave along an infinite line can be illustrated graphically by plotting $v_s\varepsilon^{-(\beta + j\alpha)x}$ on polar co-ordinates. See Fig. 270 giving such a curve for a 20-lb. cable pair with loading (44 mH. coils at 2 000 yd. spacing). The explanation of the curve is as follows.

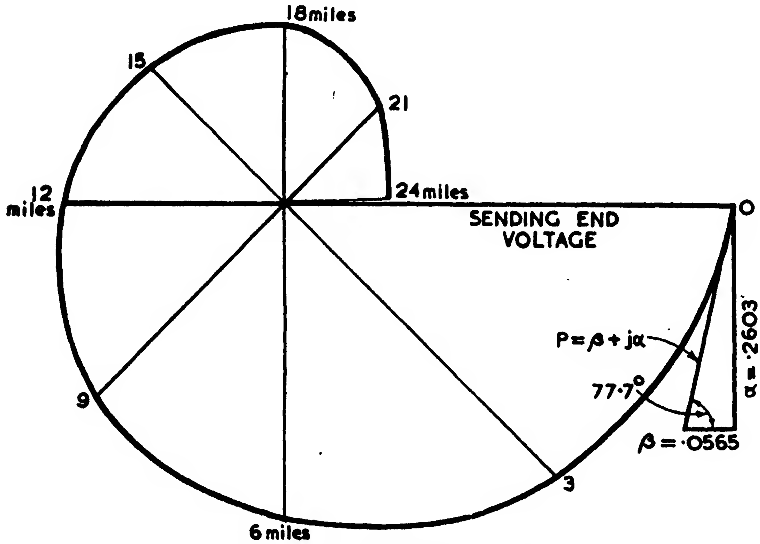


Fig. 270. Logarithmic Spiral

The radius vector decreases logarithmically in length and at the same time is rotated at a uniform rate; the resulting curve is therefore a logarithmic spiral. Now the general equation of such a spiral for a base ε is—

$$P = K\varepsilon^{-nc}$$

where K and n are constants and c is the angle of rotation of the radius.

In the practical case considered,

$P = v_x$, $K = v_s$, and c is obviously the angular rotation αx.

Then $$v_x = v_s\varepsilon^{-n\alpha x}$$

which for any value of x must give

$$v_x = v_s\varepsilon^{-\beta x}.$$

Therefore $$n = \beta/\alpha$$

and $$v_x = v_s \varepsilon(-\beta/\alpha) \cdot \alpha x,$$

from which Fig. 270 was plotted.

In graph Fig. 270, P was taken as $0{\cdot}0565 + j{\cdot}260$.

It is one of the characteristics of this curve that the angle between any radius and the tangent to the curve touching the

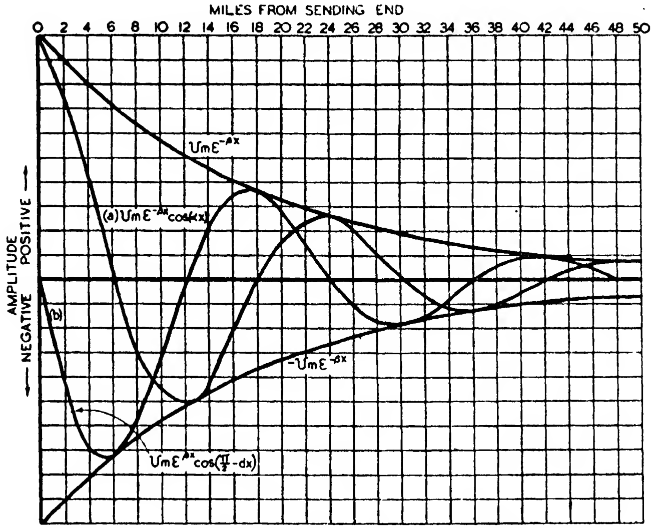


FIG. 271. ATTENUATION AND PHASE DISPLACEMENT

radius is a constant, and that the tangent of this angle is $1/n$. For the above equation therefore $1/n = \alpha/\beta$, which means that the angle of the spiral is equal to the angle of the propagation constant.

The spiral curve of Fig. 270 only gives maximum values of voltage along the line, but the sending end voltage is alternating between $+ v_s$ and $- v_s$, and therefore the voltage at all points along the line is alternating between $+ v_x$ and $- v_x$. Due however to the delay time already described, the voltage along the line at any particular instant will be

$$v_x = V_M \varepsilon^{-\beta x} \cos(\omega t - \alpha x) \qquad . \qquad . \quad (22)$$

where V_M is the peak value. The graphs in Fig. 271 show the instantaneous voltages along a line at two instants; (a) when v_s is a maximum positive and (b) when v_s is zero and about to become negative, i.e. a quarter of a cycle later.

Evaluation of β and α. The constants β and α can be evaluated in terms of the primary constants by the following method.

$$P = \beta + j\alpha = \sqrt{[(R + j\omega L)(G + j\omega C)]}.$$

$$P^2 = \beta^2 + \alpha^2 = \sqrt{[(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)]} \quad . \quad (a);$$

also
$$P^2 = \beta^2 - \alpha^2 + 2j\alpha\beta = (R + j\omega L)(G + j\omega C)$$
$$= RG + j(LG + CR) - \omega^2 LC \quad (b)$$

Now in equations of this type the real and unreal parts can be equated separately.

Using the real parts of (b)—

$$\beta^2 - \alpha^2 = RG - \omega^2 LC$$

and of (a)

$$\beta^2 + \alpha^2 = \sqrt{[(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)]}.$$

Adding: $2\beta^2 = RG - \omega^2 LC + \sqrt{[(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)]}$

$$\therefore \quad \beta = \sqrt{\tfrac{1}{2}\{\sqrt{[(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)]} + (RG - \omega^2 LC)\}} \quad (23)$$

and by subtraction:

$$\alpha = \sqrt{\tfrac{1}{2}\{\sqrt{[(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)]} - (RG - \omega^2 LC)\}} \quad (24)$$

The Direct Current Case. If only direct current is applied to the line, the propagation constant and characteristic impedance are simplified

Putting $\omega = 0$, $\qquad P = \sqrt{(RG)}$;

$$Z_o = \sqrt{\frac{R}{G}}$$

It is seen that j has vanished from the equations; that is, they are non-complex.

Therefore $\qquad P = \beta + j\alpha$

reduces to $\qquad P = \beta$.

Thus the phase constant has been eliminated and the propagation constant is simply an attenuation. The same result is obtained by putting $\omega = 0$ in (23) and (24).

Transmission Units. The term 'attenuation' has been defined by the British Standards Institution (definition number 9335) as the decrease in magnitude of the transmitted power, voltage or current due to a line or apparatus.

In telephone practice the term *transmission loss* is frequently

used to mean attenuation of power and this term will therefore be used in this book. The term is often shortened to 'loss.'

It has been shown that voltage and current along a uniform line without reflection effects are attenuated according to a simple logarithmic law. It is therefore convenient to employ a system of transmission units with a logarithmic base. By so doing the number of units expressing the transmission efficiency of such a line will be directly proportional to the length of the line, and in addition it will be possible, where the line is made up of several known sections, to find the total attenuation of a circuit by adding algebraically the transmission values of the component parts of the circuit. This latter facility can be shown mathematically as follows. If R_1, R_2, R_3, etc., represent the voltage, current or power ratios of the various sections of a circuit, then $R_1 \times R_2 \times R_3$, etc., is the overall end-to-end ratio, and if logarithms of the ratios be taken as transmission units, then,

$$\text{Log}\,(R_1 \times R_2 \times R_3 \times \ldots) = \text{Log}\,R_1 + \text{Log}\,R_2 + \text{Log}\,R_3 +, \text{etc.}$$

When the various sections of a line have different characteristic impedances there will be in addition power losses due to reflection effects, which will be dealt with later.

The Néper. For an infinite line or a line terminated with its characteristic impedance equations (10) and (11) give

$$i_x/i_s \text{ or } v_x/v_s = \varepsilon^{-\beta x}.$$

$$\therefore \quad \beta x = \log_\varepsilon (v_s/v_x) \text{ or } \log_\varepsilon (i_s/i_x).$$

βx is therefore a convenient measure of the circuit (see p. 334); it is known as the *attenuation length* and is expressed in népers or natural units. One néper therefore gives a voltage or current ratio of $\varepsilon = 2{\cdot}718$. The total attenuation of a circuit in népers is thus

$$i_s/i_x = v_s/v_x = \varepsilon^{\text{népers}}.$$

$$\left.\begin{aligned} &\text{Attenuation in népers} = \text{Log}_\varepsilon\,(v_s/v_x) \\ &\text{or, if common logarithms be used} \\ &\qquad\qquad = \text{Log}_{10}\,(v_s/v_x) \times 2{\cdot}303 \end{aligned}\right\} \quad (25)$$

When attenuation is evaluated from the primary constants the result is in népers. A transmission of one-tenth of a néper is known as a *deci-néper*, but there is no necessity for this smaller unit and it is rarely used in practice. The unit is sometimes

known as the *hyp* and a graph showing the transmission level along a repeatered circuit is known as a *hypsograph*.

The néper is the unit of transmission used by most of the continental telephone administrations.

The Decibel. The unit used in this country and in America is the *decibel* or *transmission unit*. It expresses *power* ratio on a common logarithmic basis. The primary unit is the *bel*, the decibel (db.) being one-tenth of this. The loss of a circuit in bels is therefore

$$\text{Bels} = \text{Log } 10\,(W_s/W_x)$$

or

$$\text{decibels} = 10 \text{ Log } 10\,(W_s/W_x).$$

On an infinite line or a line terminated with its characteristic impedance, the voltage and current obey the same law ε^{-Px} and it follows that the power is attenuated according to the square of this law.

Therefore loss in decibels $= 20 \text{ Log}_{10}\,(v_s/v_x)$ or $20 \text{ Log}_{10}\,(i_s/i_x)$.

It will be seen that whereas the néper can strictly only be used for lines or networks in which the voltage and current obey the same law, i.e. when $v_s/v_x = i_s/i_x$, or expressed another way, where the sending end impedance equals the receiving end impedance (i.e. when $v_s/i_s = v_x/i_x$) the decibel is not so restricted. In practice, however, it is usual to find attenuations in decibels by taking voltage measurements only, by arranging or assuming a constant impedance, usually 600 ohms.

The decibel is of universal application and is much used in radio and acoustical engineering.

Standard Cable Equivalent. Standard cable is a hypothetical type of cable having the following values per mile for the primary constants.

	British Standard Mile	American Standard Mile
R	88 ohms	88 ohms
L	1 mH.	0
G	1 micromho	0
C	0·054 μF.	0·054 μF.

The standard cable equivalent (S.C.E.) of a circuit is the length of standard cable which will give the same volume efficiency by comparative speech tests. The attenuation

constant for standard cable varies with frequency and it thus contains a distortion factor. It has, however, been used as an attenuation standard by taking its value of β at the mean speech frequency of 800 cycles per sec. This was known as the 800 *cycle mile.*

The British Standard Mile has the following values for the secondary constants at 800 cyc.

Attenuation constant . . .	0·106 hyp.
Wavelength constant . . .	0·112 radian
Propagation constant . . .	$0{\cdot}154\underline{/46^\circ}$
Characteristic impedance . . .	$571\overline{\backslash 43^\circ}$

From the attenuation constant we get

$$v_x/v_s = \varepsilon^{-0\cdot106 \times \text{S.C.E.}}$$

$$\therefore \quad 0{\cdot}106 \text{ S.C.E.} = \log_\varepsilon (v_s/v_x).$$

$$\left.\begin{aligned} \text{S.C.E.} &= 9{\cdot}42 \log_\varepsilon (v_s/v_x) \quad . \\ &= 21{\cdot}7 \log_{10} (v_s/v_x) \quad . \\ &= 10{\cdot}85 \log_{10} (W_s/W_x) \end{aligned}\right\} \qquad (27)$$

The American Standard Mile has an attenuation constant of 0·109, the higher value being due to the absence of inductance.

The use of standard cable has been abandoned in favour of the decibel, chiefly on account of the variation of β with frequency. It has some advantage as a standard so long as voice-ear methods of measurement are employed, but when attenuation measurements at individual frequencies throughout the frequency range are required Standard Cable Equivalent loses its significance and the 800 cycle mile has given way to the much simpler unit, the decibel. Single frequency alternating current methods of measurement are now universally employed on account of their precision and speed.

Relationship between Transmission Units. The three units of transmission, néper, 800 cycle mile, and decibel can be related to one another for the same impedance conditions from equations (25), (26), and (27).

$$\begin{aligned} v_s/v_x &= 10^{\text{db.}/20} = 10^{\text{népers}/2\cdot303} = 10^{\text{S.C.E.}/21\cdot7} \\ &= \varepsilon^{0\cdot115\text{db.}} = \varepsilon^{\text{népers}} = \varepsilon^{0\cdot106\text{S.C.E.}} \\ W_s/W_x &= 10^{\text{db.}/10} = 10^{\text{népers}/1\cdot15^*} = 10^{\text{S.C.E.}} \\ &= \varepsilon^{0\cdot23\text{db.}} = \varepsilon^{2\cdot\text{népers}} = \varepsilon^{0\cdot212\text{S.C.E.}} \end{aligned}$$

Therefore,

$$\left.\begin{aligned}\text{Népers} &= \text{db.} \times 0{\cdot}115 \\ &= \text{S.C.E.} \times 0{\cdot}106\end{aligned}\right\} \quad . \quad . \quad (28a)$$

$$\left.\begin{aligned}\text{Db.} &= \text{Népers} \times 8{\cdot}686 \\ &= \text{S.C.E.} \times 0{\cdot}922\end{aligned}\right\} \quad . \quad . \quad (28b)$$

$$\left.\begin{aligned}\text{S.C.E.} &= \text{Népers} \times 9{\cdot}42 \\ &= \text{Db.} \times 1{\cdot}085\end{aligned}\right\} \quad . \quad . \quad (28c)$$

Artificial Line Networks. It is frequently necessary in transmission work and particularly in connection with testing

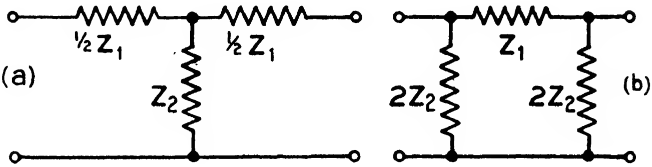


FIG. 272. 'T' AND 'π' NETWORKS

apparatus to make use of electrical networks which are equivalent to real lines at a particular frequency so far as attenuation and terminal impedances are concerned. The theory of equivalent circuits also gives an extremely simple method of solving many transmission problems concerning terminal conditions only, as will be shown later.

There are two networks commonly used, in both of which let Z_1 represent the total series impedance and Z_2 the total shunt impedance. They are—

(*a*) The 'T' or *mid-series* network made up of three impedances as shown in Fig. (272*a*) and

(*b*) The 'Π' (pi) or *mid-shunt* network made up of three impedances as shown in Fig. (272*b*).

The 'T' Network. If the network impedance Z_1 is made equal to the total series impedance of the line $(R + j\omega L)x$ and the network impedance Z_2 equal to the total shunt impedance of the line $1/(G + j\omega C)x$, what is known as a *nominal 'T'* circuit is obtained, as shown in Fig. 273 (*a*). Such a network will not have exactly the same characteristics as the real line it is supposed to represent because of the lumping of the leakance at the centre of the series impedance. The difference will be considerable if the attenuation is large. To make an

exact equivalent, the values of Z_1 and Z_2 will have to be modified, and the modified values can be expressed in terms of the characteristic impedance and propagation constant required. The resulting network is known as an *equivalent 'T'* circuit. (See Fig. 273 (*b*).)

The values of Z_1 and Z_2 shown in Fig. 272 can be proved as

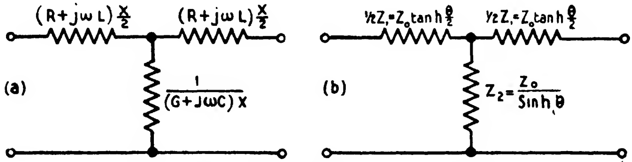


FIG. 273. EQUIVALENT 'T' NETWORK

follows. Let the network Fig. 272 (*a*) be closed with its characteristic impedance Z_o; let i_s and i_x be the sent and received currents (see Fig. 274).

Since $(\frac{1}{2}Z_1 + Z_o)$ is in parallel with Z_2,

$$Z_s = \tfrac{1}{2}Z_1 + \frac{Z_2(\frac{1}{2}Z_1 + Z_o)}{\frac{1}{2}Z_1 + Z_2 + Z_o} \quad . \quad . \quad (a)$$

The line is correctly terminated and $Z_s = Z_o$, therefore

$$Z_o = \sqrt{[Z_1Z_2(1 + Z_1/4Z_2)]} \quad . \quad . \quad (29)$$

Because the line is equivalent to a uniform line correctly terminated

$$i_x = i_s\varepsilon^{-Px} = i_s\varepsilon^{-\theta}$$

and

$$i_x = \frac{Z_2}{\frac{1}{2}Z_1 + Z_2 + Z_o}\, i_s$$

$$\therefore \ \varepsilon^{-\theta} = \frac{Z_2}{\frac{1}{2}Z_1 + Z_2 + Z_o} \quad . \quad . \quad . \quad (b)$$

$$\theta = \log_\varepsilon \frac{\frac{1}{2}Z_1 + Z_2 + Z_o}{Z_2} \quad . \quad . \quad (30)$$

Substituting (*b*) in (*a*);

$$Z_o = \tfrac{1}{2}Z_1 + \varepsilon^{-\theta}(\tfrac{1}{2}Z_1 + Z_0)$$

or

$$\tfrac{1}{2}Z_1 = Z_o\left(\frac{1 - \varepsilon^{-\theta}}{1 + \varepsilon^{-\theta}}\right) = Z_o\left(\frac{\varepsilon^{\theta/2} - \varepsilon^{-\theta/2}}{\varepsilon^{\theta/2} + \varepsilon^{-\theta/2}}\right)$$

$$\therefore \ \tfrac{1}{2}Z_1 = Z_o \tanh \theta/2 \quad . \quad . \quad . \quad . \quad (31)$$

Substituting the value of $\frac{1}{2}Z_1$ in (b) gives

$$\varepsilon^{-\theta} = \frac{Z_2}{Z_2 + Z_o\left(1 + \dfrac{1 - \varepsilon^{-\theta}}{1 + \varepsilon^{-\theta}}\right)} = \frac{Z_2}{Z_2 + \dfrac{2Z_o}{1 + \varepsilon^{-\theta}}}$$

$$\therefore\ Z_2 = \frac{2Z_o}{(\varepsilon^{\theta} - 1)(\varepsilon^{-\theta} + 1)}$$

$$= Z_o/\sinh\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

Another useful identity which can be obtained is

$$\tfrac{1}{2}Z_1 + Z_2 = Z_o \coth\theta \quad . \quad . \quad . \quad (33)$$

Since $$\tfrac{1}{2}Z_1 + Z_2 = \frac{2Z_o}{\varepsilon^{\theta} - \varepsilon^{-\theta}} + Z_o\left(\frac{1 - \varepsilon^{-\theta}}{1 + \varepsilon^{-\theta}}\right)$$

$$= \frac{Z_o(1 + \varepsilon^{-\theta} + \varepsilon^{\theta} + \varepsilon^{-2\theta})}{(\varepsilon^{\theta} - \varepsilon^{-\theta})(1 + \varepsilon^{-\theta})} = Z_o \coth\theta$$

The 'Π' Network. *Nominal* and *equivalent* 'Π' networks can be found in the same way as the 'T' networks (see Fig. 275 (a) and (b)).

The following identities can be found for the equivalent 'Π' network.

$$\left.\begin{aligned}
\varepsilon^{-\theta} &= \frac{2Z_2}{Z_1 + Z_o\left(1 + \dfrac{Z_1}{2Z_2}\right)} \\
Z_o &= \sqrt{Z_1 Z_2\left(\dfrac{1}{1 + \dfrac{Z_1}{4Z_2}}\right)} \\
\operatorname{Cosh}\theta &= 1 + \frac{Z_1}{2Z_2}
\end{aligned}\right\} \quad (34)$$

The latter identity also applies to the equivalent 'T' network.

Non-reactive Networks. The artificial lines most used in practice are non-reactive, that is, they are made up of simple resistances without inductance or capacitance. They are termed *attenuators* or *pad circuits*. Reactive networks are used when it is necessary to correct a circuit for unequal attenuation at different frequencies. These networks are then known as *attenuation equalizers* and are dealt with in Chapter XVI.

TABLE I

ELEMENTS OF NON-REACTIVE NETWORKS
(Z_o = 600 ohms)

Decibels	θ	'T' Network		'Π' Network	
		$\frac{1}{2}Z_1$	Z_2	Z_1	$2Z_2$
1	0·115	34·46	5 206	69·2	10 430
2	0·230	68·76	2 583	139	5 236
3	0·345	102·6	1 703	211	3 509
4	0·460	136	1 258	286	2 651
5	0·576	168	987	365	2 143
6	0·691	199	803	448	1 866
7	0·806	229	670	538	1 569
8	0·921	258	568	634	1 394
9	1·036	286	489	737	1 260
10	1·151	312	422	854	1 155
11	1·266	336	368	979	1 071
12	1·381	359	322	1 118	1 002
13	1·496	380	283	1 272	947
14	1·611	400	250	1 442	899
15	1·727	419	221	1 633	860
16	1·842	436	189	1 845	826
17	1·957	451	173	2 081	798
18	2·072	466	154	2 344	772
19	2·189	479	137	2 639	752
20	2·302	491	122	2 968	733

When inductance and capacitance are eliminated the equations for characteristic impedance and propagation constant are reduced to

$$Z_o = \sqrt{(R/G)};$$
$$P = \beta = \sqrt{(RG)}.$$

These constants are now a simple resistance and an attenuation without phase change respectively, and they are constant for all frequencies.

Table I shows the values of the resistances required to make up 'T' and 'Π' networks with 1 to 20 db. loss and 600 ohms characteristic impedance. They have been calculated from equations (31) and (32) for the 'T' network and from the identities shown in Fig. 275 for the 'Π' network.

Use of Artificial Line Diagrams. By the aid of artificial line diagrams (Figs. 273 (*b*) and 275 (*b*)), which are equivalent to a real line for all terminal conditions, many transmission

problems can be solved without resorting to the fundamental equations (13) and (14). Two examples will now be given, and the results will be useful in considering reflection effects later.

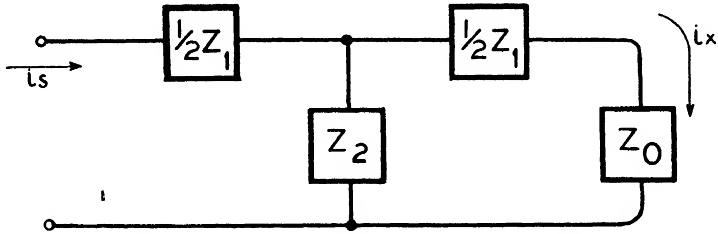


FIG. 274. 'T' NETWORK TERMINATED BY Z_0

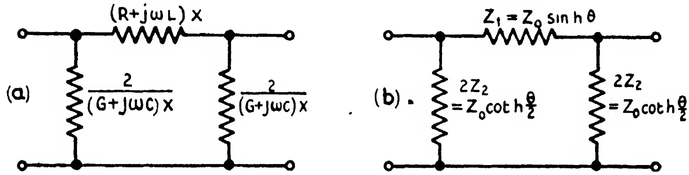


FIG. 275. EQUIVALENT 'π' NETWORK

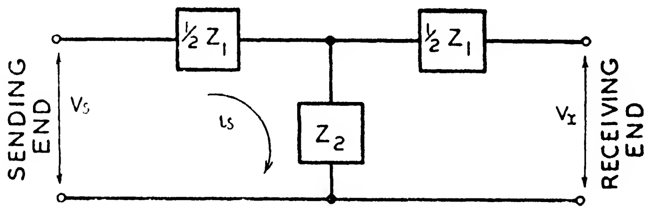


FIG. 276. 'T' NETWORK, OPEN CIRCUITED

Voltage at the Receiving End of a line when Open-circuited. The artificial 'T' line diagram for this condition is shown in Fig. 276.

Since there is no current flowing to the receiving end, the value of v_x is the same as the voltage across Z_2.

$$v_x = v_s \,.\, Z_2/(\tfrac{1}{2}Z_1 + Z_2).$$

Substituting from equations (32) and (33)

$$v_x = v_s/\sinh\theta \coth\theta$$

$$= v_s/\cosh\theta \quad . \quad . \quad . \quad . \quad (36)$$

If θ is large, $\cosh\theta = \varepsilon^\theta/2$.

Therefore if the line is long

$$v_x = 2v_s\varepsilon^{-\theta}$$

which is twice the voltage that would be obtained at point x on a line infinitely extended, or closed with Z_o. This effect of double voltage at the open end of a long line is encountered in transmission testing, and will be referred to later.

Current at the Receiving End of a Line when Short-circuited. The artificial 'T' line diagram for this condition is given in Fig. 277.

$$i_x = i_s \,.\, Z_2/(\tfrac{1}{2}Z_1 + Z_2) = i_s.\frac{Z_o/\sinh\theta}{Z_o\coth\theta} = \frac{i_s}{\cosh\theta} \quad . \quad . \quad (37)$$

also
$$i_x = \frac{v_s}{\tfrac{1}{2}Z_1 + \dfrac{\tfrac{1}{2}Z_1Z_2}{\tfrac{1}{2}Z_1 + Z_2}} \times \frac{Z_2}{\tfrac{1}{2}Z_1 + Z_2}$$

$$= \frac{v_sZ_2}{(\tfrac{1}{2}Z_1)^2 + Z_1Z_2} = \frac{v_s}{Z_o^2}Z_2.$$

Substituting from equations (29) and (32)

$$i_x = v_s/Z_o\sinh\theta \quad . \quad . \quad . \quad (38)$$

If θ is large, $\sinh\theta = \varepsilon^{\theta}/2$

Therefore $i_x = 2v_s\varepsilon^{-\theta}/Z_o$,

which is twice the value that would be obtained if the line were terminated with Z_o.

Total Reflection. The phenomena of double voltage and double current at the open and closed ends respectively of a long line can be explained as follows. The wave of energy travels along the line with a finite velocity, and on reaching the receiving end is totally reflected either by a disconnection or a short circuit; in the former case the voltage is reflected in phase giving double voltage, and the current is reflected 180° out of phase resulting in zero current; in the second case the voltage is reflected out of phase and the current in phase. The short circuit therefore produces the exact opposite effect from that produced by a disconnection.

Multiple Reflections. The effect discussed in the previous paragraph was derived from equations (36) and (38) on the assumption that the line was long, i.e. only the first reflection at the receiving end was taken into account.

If the line cannot be regarded as infinite, then multiple reflections take place between the two ends of the circuit. Take the case of a finite line disconnected at the receiving end and with a voltage applied at the sending end from some

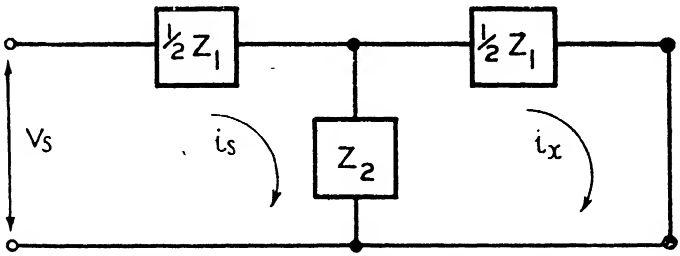


FIG. 277. 'T' NETWORK, SHORT CIRCUITED

apparatus with negligible impedance. (See Fig. 278.) The incident wave will reach the receiving end with the value $v_s\varepsilon^{-\theta}$, it will then be totally reflected giving twice this value,

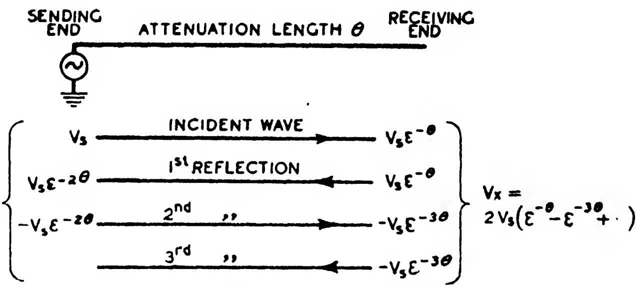


FIG. 278 MULTIPLE REFLECTIONS

and be returned to the sending end. Here reflection will take place out of phase and it will again reach the receiving end, this time with the value $-\ v_s\varepsilon^{-3\theta}$, this process being repeated *ad infinitum*.

The total voltage v_x after an infinite number of reflections will be

$$v_x = 2v_s(\varepsilon^{-\theta} - \varepsilon^{-3\theta} + \varepsilon^{-5\theta} - \varepsilon^{-7\theta} \ldots$$
$$= 2v_s\varepsilon^{-\theta}\,(1 - \varepsilon^{-2\theta} + \varepsilon^{-4\theta} \ldots)$$

This is a geometric series of the form

$$a + ar + ar^2 + ar^3 \ldots ar^{n-1}.$$

The sum to n terms of such a series is

$$a\,\frac{1 - r^n}{1 - r}$$

and the sum to infinity is

$$a/(1 - r).$$

In the above expression $a = 2v_s\varepsilon^{-\theta}$, $r = -\varepsilon^{-2\theta}$; therefore all the reflections to infinity give

$$\begin{aligned} v_x &= 2v_s\varepsilon^{-\theta}/(1 - \varepsilon^{-2\theta}) = 2\,.\,v_s/(\varepsilon^{\theta} - \varepsilon^{-\theta}), \\ &= v_s/\cosh\theta, \end{aligned}$$

which is the same as equation (36).

Therefore by using hyperbolic functions all reflection effects are automatically taken into account.

The transmission of energy along a telephone line has already been explained as a wave motion, and the reflection effects described above fit in with this wave theory. Similar reflection effects occur with other forms of wave motion, e.g. in the wave motion which takes place on the surface of water or in the wave motion which can be produced along a taut string.

Long Lines. Equations (15) and (16) give the sending end impedances of a finite line when the receiving end is short-circuited and open-circuited respectively.

$$Z_{sc} = Z_0 \tanh\theta \quad . \quad . \quad . \quad (15)$$

$$Z_{so} = Z_0 \coth\theta \quad . \quad . \quad . \quad (16)$$

When the line is electrically long, i.e. when θ is large, $\tanh\theta$ and $\coth\theta$ approximate to unity, and the sending end impedance becomes equal to the characteristic impedance. The short circuit and the open circuit are of course the limiting conditions of terminal impedance, and thus when the line is long electrically the terminal condition at the distant end has no effect upon the sending end impedance, current, and voltage. If equations (15) and (16) are plotted as in Fig. 279 we see what value of attenuation length gives a reasonable approximation to an infinite line. Fig. 279 has been plotted to show Z_s/Z_0 against length of line and attenuation length for a 20 lb. cable circuit loaded with 44 mH. at 2 000 yd., propagation constant

$$P = 0{\cdot}266\underline{/77{\cdot}6^\circ} = 0{\cdot}0565 + j{\cdot}260.$$

Graphs of tanh θ and coth θ for non-complex values of θ have already been given in Fig. 269, and similar curves for tanh βl and coth βl, the real part of the propagation constant, are given in Fig. 279. When the complex nature of P is taken into account, tanh Pl and coth Pl become oscillatory curves between

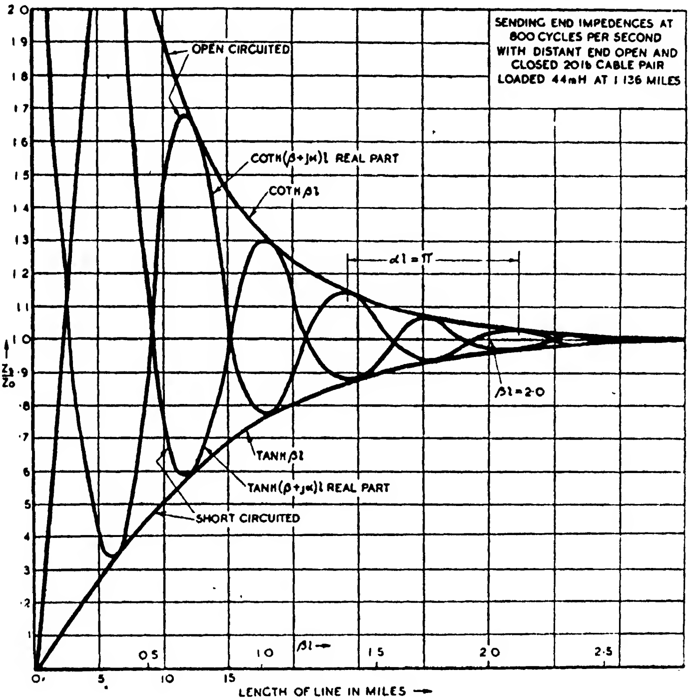


FIG. 279. SENDING-END IMPEDANCES FOR OPEN AND SHORT CIRCUITED LINES

the two smooth curves of tanh βl and coth βl. It will be seen from this graph that a line having a value for βl exceeding 2, i.e. 2 népers, can reasonably be regarded as an infinite line. The graph, Fig. 279, also demonstrates the advantage of using hyperbolic functions, for the simple expressions tanh Pl and coth Pl represent the complex oscillatory curves and in addition include oscillatory and decreasing phase angles not shown by the graph.

Partial Reflection. It has been shown how, when a line is terminated with a short circuit or a disconnection, the whole

of the energy is reflected, and also that when a line is terminated by an impedance equal to its characteristic impedance no reflection takes place, all the energy being absorbed by the terminal impedance. When any other value of impedance is used to terminate the line the phenomenon of partial transmission and partial reflection is experienced. This is the condition which usually occurs in practice. Terminal apparatus is designed to have an impedance as nearly as possible equal

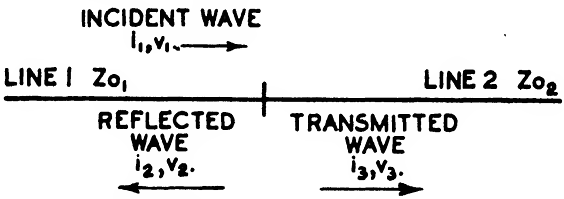


FIG. 280. REFLECTION EFFECTS DUE TO CHANGE OF LINE IMPEDANCE

to that of the line so that it will absorb the maximum of power, but a certain difference in impedance must occur, giving rise to partial reflections.

Partial reflection will now be investigated mathematically. Take the case of a line with a characteristic impedance of Z_{o_1} connected to another line with an impedance Z_{o_2} (see Fig. 280). Assume also that both lines are long enough to eliminate multiple reflections.

Let v_1, i_1 be the values of the incident wave which would exist at the junction if $Z_{o_1} = Z_{o_2}$.

Let v_2, i_2 be the values for the reflected wave, let also v_3, i_3 be the values for the transmitted wave. Then since the incident wave divides into reflected and transmitted waves

$$v_3 = v_1 - v_2 \quad . \quad . \quad . \quad . \quad (a)$$

$$i_3 = i_1 - i_2 \quad . \quad . \quad . \quad . \quad (b)$$

It has already been explained for the limiting conditions that when the voltage is reflected in phase the current is reflected out of phase, and vice versa. Therefore v_2 is always of opposite sign to i_2 and

$$i_1 Z_{o_1} = v_1,$$

$$i_2 Z_{o_1} = -v_2,$$

$$i_3 Z_{o_2} = v_3.$$

From (*b*)

$$i_1 - i_2 = i_3 = v_3/Z_{o_2},$$

but $$v_3/Z_{o_2} = i_1 Z_{o_1}/Z_{o_2} + i_2 Z_{o_1}/Z_{o_2} \qquad \text{from } (a)$$

Therefore $(i_1 + i_2)Z_{o_1} = (i_1 - i_2)Z_{o_2}$.

If m is the coefficient of reflection of current

$$(1 + m)Z_{o_1} = (1 - m)Z_{o_2}$$

$$\therefore \quad m = (Z_{o_2} - Z_{o_1})/(Z_{o_1} + Z_{o_2}) \qquad . \ (39a)$$

Similarly from (*a*)

$$v_1 - v_2 = v_3 = i_3 Z_{o_2}.$$

But $$i_3 Z_{o_2} = Z_{o_2}(v_1/Z_{o_1} + v_2/Z_{o_1}) \qquad \text{from } (b)$$

$$\therefore \quad Z_{o_2}(v_1 + v_2) = Z_{o_1}(v_1 - v_2).$$

If m_1 is the coefficient of reflection of voltage,

$$Z_{o_2}(1 + m_1) = Z_{o_1}(1 - m_1)$$

$$\therefore \quad m_1 = (Z_{o_1} - Z_{o_2})/(Z_{o_1} + Z_{o_2}) \qquad . \quad . \ (39b)$$

The two coefficients are thus of the same value but of opposite sign.

The coefficient of *transmission* of voltage will be

$$1 - m_1 = 2Z_{o_2}/(Z_{o_1} + Z_{o_2}). \qquad . \quad . \ (39c)$$

The coefficient of transmission of current

$$1 - m = 2Z_{o_1}/(Z_{o_1} + Z_{o_2}) \qquad . \quad . \ (39d)$$

The coefficient of transmission of volt-amperes will be

$$(1 - m)(1 - m_1) = 4Z_{o_1}Z_{o_2}/(Z_{o_1} + Z_{o_2})^2 \qquad . \ (39e)$$

It should be noted that the equations (39*a*) to (39*e*) are vector quantities; the modulus representing the coefficient of reflection or transmission whilst the angle represents a phase change. In the case of (39*e*) the angle might be described as representing a phase shift of volt-amperes, but it is of no practical significance and in obtaining the next two formulæ concerned with power only the modulus of (39*e*) is required.

The power in the infinite line condition is $W_1 = v_1 i_1 \cos \phi_1$, where ϕ_1 is the angle of the impedance Z_{o_1}. The power in Z_{o_2} with angle ϕ_2 is

$$W_2 = v_1 i_1 \left| \frac{4Z_{o_1}Z_{o_2}}{(Z_{o_1} + Z_{o_2})^2} \right| \cos \phi_2 \qquad . \quad . \ (40)$$

The ratio of these two powers W_1/W_2 gives the transmission loss which can be expressed in decibels.

$$\text{Loss} = 10 \log_{10}\left(\frac{(Z_{o_1} + Z_{o_2})^2}{4Z_{o_1}Z_{o_2}} \cdot \frac{\cos \phi_1}{\cos \phi_2}\right)$$

$$= 10 \log_{10}\left|\frac{(Z_{o_1} + Z_{o_2})^2}{4Z_{o_1}Z_{o_2}}\right| + 10 \log_{10} \frac{\cos \phi_1}{\cos \phi_2} \quad . \quad (41)$$

Terminal Loss and Terminal Gain. When Z_{o_2} represents the impedance of some apparatus terminating the line Z_{o_1} then equation (41) gives what is known as the *terminal loss.* This need not, however, be an actual loss *compared with the infinite line condition.* As an example take the case of an unloaded cable circuit with an impedance of $570/\overline{43^\circ}$ ohms terminated with a telephone having an impedance of $450/\underline{35^\circ}$.

Then $$Z_{o_1} = 570/\overline{43^\circ} = 417 - j389$$

$$Z_{o_2} = 450/\underline{35^\circ} = 369 + j258$$

$$Z_{o_1} + Z_{o_2} = 786 - j131 = 797/\overline{9^\circ}$$

$$\therefore \quad \frac{(Z_{o_1} + Z_{o_2})^2}{4Z_{o_1}Z_{o_2}} = \frac{797^2}{4,570,450} = 0{\cdot}62$$

$$\text{Cos } \phi_1/\cos \phi_2 = 0{\cdot}731/0{\cdot}819 = 0{\cdot}89$$

$$\therefore \quad \text{Loss} = 10 \log (0{\cdot}62 \times 0{\cdot}89) = -2{\cdot}57 \text{ db.}$$

The terminal loss in this case is a negative quantity, i.e. a gain of 2·57 db.

A further examination of equation (41) reveals that *any* difference in the phase angles will give a reduction in $(Z_{o_1} + Z_{o_2})$ which results in a terminal gain in volt-amperes, and if one angle is of opposite sign and not greater than the other there will be a considerable gain in power. Any difference in the magnitudes of $Z_{o_1} + Z_{o_2}$ results in a loss of power. Z_{o_1} and Z_{o_2} from the above example are drawn in Fig. 281, which shows why the phase difference is beneficial. Solving the triangle in Fig. 281 by the Cosine Rule

$$(Z_{o_1} + Z_{o_2})^2 = Z_{o_1}^2 + Z_{o_2}^2 - 2\, Z_{o_1}Z_{o_2} \cos (180 - \phi + \phi_2)$$

$$= Z_{o_1}^2 + Z_{o_2}^2 + 2\, Z_{o_1}Z_{o_2} \cos (\phi_1 - \phi_2)$$

Equation (41) can now be written

$$\text{Loss} = 10 \log_{10} \left\{ \left[\frac{Z_{o_1}{}^2 + Z_{o_2}{}^2 + 2Z_{o_1}Z_{o_2} \cos(\phi_1 - \phi_2)}{4Z_{o_1}Z_{o_2}} \right] \frac{\cos \phi_1}{\cos \phi_2} \right\}$$

Putting $r = Z_{o_1}/Z_{o_2}$ and $\psi = \phi_1 - \phi_2$;

$$\text{Loss} = 10 \log_{10}\{\tfrac{1}{4}(r + 1/r + 2\cos\psi)\} + 10 \log_{10} \frac{\cos \phi_1}{\cos \phi_2} \quad (42)$$

Fig. 282A gives a series of curves of the first factor of (42), i.e. the terminal loss in volt-amperes for values of r from 0·1

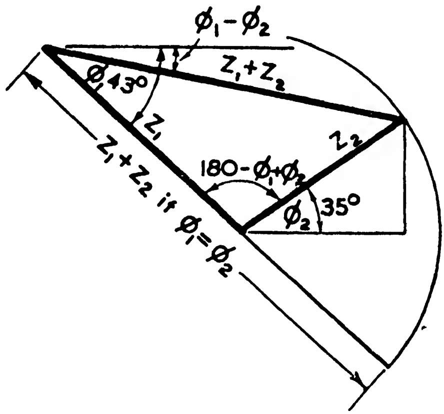


FIG. 281. IMPEDANCE VECTOR FOR TERMINATION

to 1·0 and values of ψ from 0°–90°. By adding the second factor of 10 log ($\cos \phi_1/\cos \phi_2$) from Fig. 282B, the true power loss is obtained.

Telephone instrument circuits are designed so that they have an impedance approximately equal to that of the lines to which they are normally connected, but with opposite phase angle. The values in the preceding example are typical. The desired telephone impedance is obtained by the introduction of the induction coil (see Chapter II). A terminal gain can thus be expected on local telephone lines but its value is usually small on account of the shortness of the lines.

Condition for Maximum Power in Terminal Apparatus. Consider the case of a line terminated with apparatus of impedance Z_2/ϕ_2. If the line is long with a characteristic impedance $Z_1/\overline{\phi_1}$ the sending end voltage will not be affected

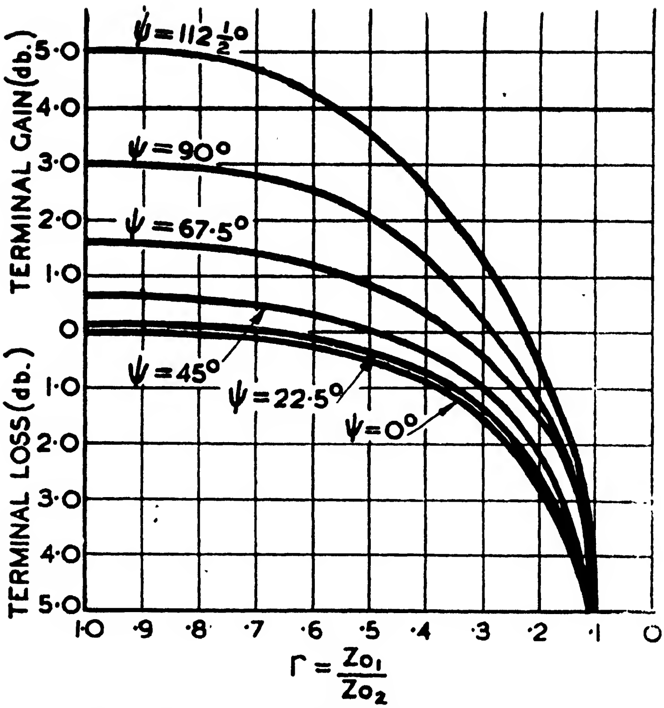


FIG 282A. EFFECT OF IMPEDANCE ON TERMINAL LOSS OR GAIN

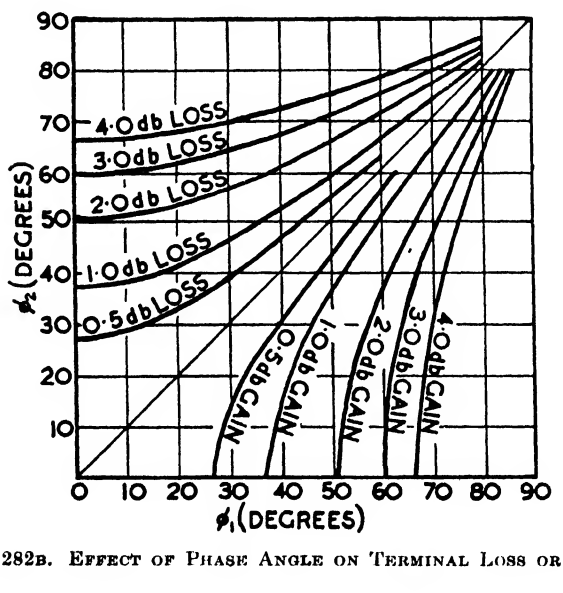


FIG. 282B. EFFECT OF PHASE ANGLE ON TERMINAL LOSS OR GAIN

by any change in Z_2 and it can therefore be regarded as a generator of impedance $Z_1\underline{/\phi_1}$ (see Fig. 283).

$$\text{Power in } Z_2 = \frac{v^2 Z_2}{(Z_1 + Z_2)^2} \cos \phi_2,$$

$$\text{or } W = \frac{v^2 R_2}{(R_1 + R_2)^2 + (X_1 + X_2)^2}$$

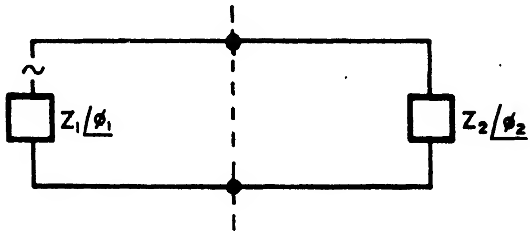


FIG. 283. CONDITIONS FOR MAXIMUM POWER

If the reactance of Z_2 is variable maximum power is obviously obtained when

$$X_1 = - X_2.$$

Then $$W = v^2 R_2/(R_1 + R_2)^2.$$

By differentiating it is found that W is a maximum when

$$R_1 = R_2.$$

Therefore for maximum power

$$R_1 + jX_1 = R_2 - jX_2$$

or $$Z_1\underline{/\phi_1} = Z_2\overline{\backslash\phi_2} \quad . \quad . \quad . \quad . \quad (43)$$

Z_2 is then known as the *conjugate impedance of* Z_1.

Use of Transformers for Impedance Matching. When it is necessary to connect a line to apparatus with a different impedance the terminal loss in volt-amperes can be eliminated by using a transformer of suitable ratio. The transformer itself will of course introduce certain losses which will to some extent nullify the advantage obtained by its use.

In accordance with transformer theory the turns ratio of the transformer must be $\sqrt{(Z_1/Z_2)}$. The transformer will not of course after the angles of the impedances except for small changes due to losses in the transformer. Referring to equation

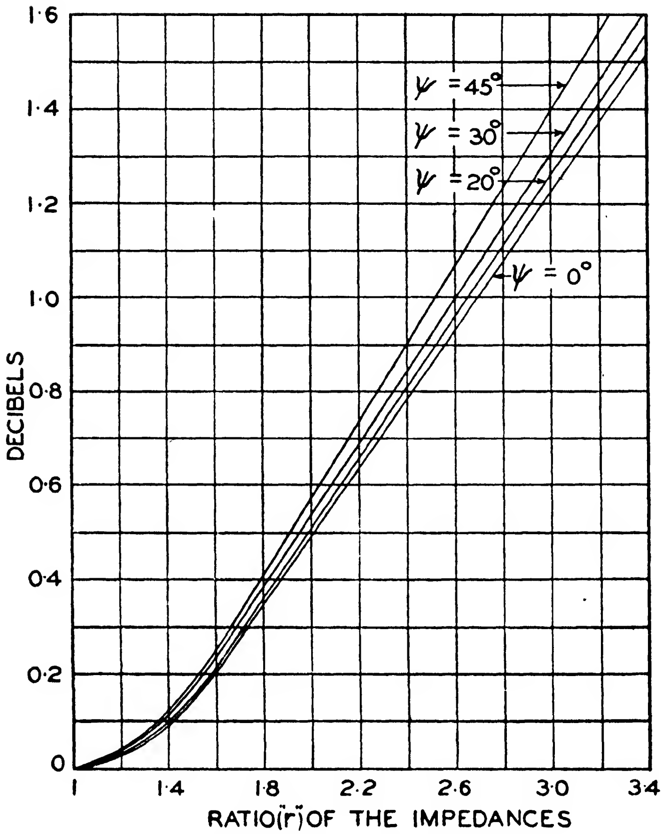


FIG. 284. TRANSMISSION GAIN WITH AN IDEAL TRANSFORMER

(42), r will be reduced to unity and the gain in power by introducing the transformer will be

$$\text{Gain} = 10 \log_{10} \left\{ \frac{\frac{1}{4}\left(r + \frac{1}{r} + 2 \cos \psi\right)}{\frac{1}{4}(2 + 2 \cos \psi)} \right\}$$

$$= 10 \log_{10} \left(\frac{1 + r^2 + 2r \cos \psi}{2r (1 + \cos \psi)} \right). \qquad (44)$$

This transformer gain is plotted in Fig. 284 for values of r from 1·0 to 3·4 and ψ from 0°–45°.

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CHAPTER XV

LINE CHARACTERISTICS AND LOADING

BEFORE applying the transmission theory given in the preceding chapter to practical line problems, first consider the various types of circuits used.

Single-wire Circuits. Equations (1) and (2) and the subsequent theory were derived for a single-wire circuit having primary constants of R ohms per mile single-wire resistance neglecting the resistance of the earth return, L henries self-inductance per mile, G mhos leakance to earth per mile, and C farads capacitance to earth per mile.

A line of this nature does not give a satisfactory telephone circuit if there are other telephone or telegraph wires in close proximity which will give rise to electrostatic and electromagnetic disturbance resulting in 'overhearing.' Power circuits may also produce inductive disturbance which will seriously interfere with such telephone circuits. Single-wire circuits are, however, sometimes used in remote districts, and give excellent transmission.

Loop Circuits. To avoid the inductive disturbances to which single-wire circuits are liable, the earth return is replaced by a second wire thus forming a loop circuit. Provided that the two wires of the line have the same constants, the currents induced in them from any disturbing circuit will neutralize each other and produce no effect in the telephones at the end of the line. Fig. 285 shows diagrammatically the effect of induced current in a loop circuit.

In the case of aerial circuits the leakance varies considerably according to weather conditions, but so long as the leakance from both wires is approximately equal inductive disturbance will not be serious.

The transmission formulæ given in the preceding chapter apply equally well to loop circuits; the primary constants are then R ohms and L henries per loop mile, and G mhos and C farads per mile wire to wire. It will be appreciated that although the same gauge of wire may be used for a loop circuit as for a single-wire circuit, the primary constants will not be

the same for the two circuits and the characteristic impedances and attenuation constants will therefore be different. In practice it is found that a single-wire aerial circuit has a slightly

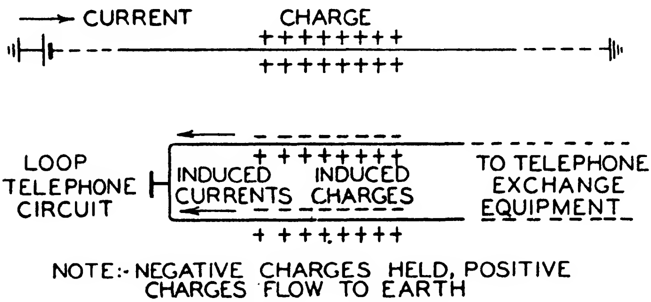


Fig. 285. Induced Currents in Loop Telephone Circuit

lower attenuation than a loop circuit, due mainly to the lower capacitance. In the case of cable circuits the attenuations of single-wire and loop circuits are approximately the same.

Phantom Circuits. It has been shown that similar currents induced in the two wires of a loop circuit produce no effect in

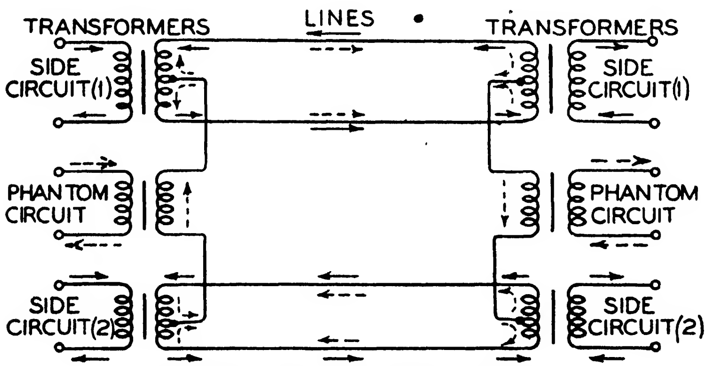


Fig. 286. Side and Phantom Circuits

the loop circuit provided that the two wires have similar characteristics. This important principle can be carried further so that from two loop circuits can be derived an additional circuit known as a *superposed* or *phantom* circuit, and the two loop circuits are then known as the *side* circuits, or *physical* circuits. Transformers are introduced as shown in Fig. 286 and the

relative directions of the currents in the side and phantom circuits are also indicated.

The two wires of each side circuit and the two halves of the line windings of the side circuit transformers must be balanced very accurately to avoid cross-talk between side and phantom circuits.

The principle of balanced currents can be carried a stage further and what is known as a *super-phantom* or *second phantom* can be obtained from two phantom circuits. The super-phantom is connected to the centre points of the phantom transformers. Again the balance of lines and transformers must be extremely accurate if cross-talk is to be avoided.

On certain submarine cables use is made of the third and fourth phantom where the degree of balance allows of this.

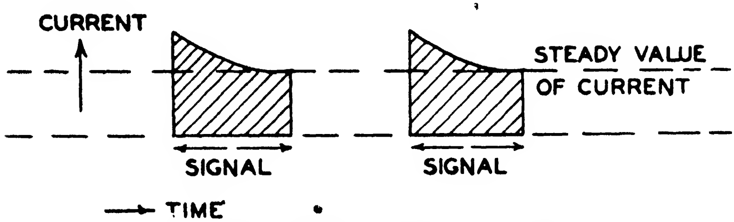


FIG. 287. DIRECT CURRENT IMPULSES

The use of phantom circuits need not of course be restricted to ordinary telephone working; they may be used for d.c. or a.c. signalling circuits, telegraph circuits, or carrier working, etc. On the main inland trunk cables in this country the second phantoms are usually used for direct-current teleprinter working.

When direct-current telegraph or signalling circuits are used superposed on telephone circuits, it is necessary to fit filter circuits which will prevent the sharp peaks of current due to the capacitance of the lines. The sharp peaks of current would occur at the commencement of each signal as indicated in Fig. 287 and a much higher standard of balance would be required than is practicable, in order to avoid interference to the telephone circuits.

Phantom circuits on aerial lines are rarely used in this country as the degree of balance required for insulation resistance makes the circuits difficult to maintain. With aerial

circuits also, the spacing of the wires is not perfectly uniform due to slight differences in tensions to which the wires are regulated. Phantom working also complicates the signalling requirements.

The transmission theory of the preceding chapter applies equally well to side and phantom circuits, but the primary constants of a phantom circuit will be different from those of the side circuits from which the phantom is derived. Examples will be given later.

The transmission formulæ which have been developed for lines with uniformly distributed constants will now be applied to the various types of aerial line used in this country.

Aerial Line Conductors. Hard-drawn copper and cadmium copper are now the only types of conductor used for aerial lines in this country. Hard-drawn copper is used for trunk lines and cadmium copper is used for subscribers' local lines and short trunk circuits. Bronze wire has been largely used in the past for subscribers' circuits, but its resistance is much higher than that of cadmium copper. Heavy gauge galvanized iron wire has also been used in the past for trunk and telegraph circuits in remote districts, and a certain amount still exists. A few constants for iron wire will therefore be given.

Conductors are designated by their weight per mile, and as the resistance per mile is inversely proportional to the weight per mile a useful constant is obtained for any conductor by multiplying the weight per mile by the resistance per mile. This constant is known as the *ohm-mile constant.*

Then

$$\text{Resistance} = \frac{\text{Ohm-mile constant.}}{\text{Weight per mile}}$$

The following is a list of ohm-mile constants—

Hard-drawn copper	878
Bronze	1 819
Cadmium copper	1 050
Iron	5 328

With alternating current the resistance of a wire is higher than with direct current and is termed the *effective resistance.* The increased resistance is due to the magnetic field which is produced within the wire itself giving rise to a back-e.m.f. which is greatest at the centre of the wire. The current density

is therefore greatest at the surface of the conductor, hence the term *skin effect*. With copper wire at ordinary telephone frequencies the effect is small, but with iron wire the large permeability makes the effect of considerable importance.

Inductance of Aerial Lines. The inductance of a loop circuit is given by the following formula—

$$L = [1 + 4 \log_e \left(\frac{D}{d}\right)] \, l \,.\, 10^{-9} \text{ henries} \quad . \quad . \quad (45)$$

where l is the length, D the distance between the wires and d the radius of the wires; all measurements being in centimetres. In the case of copper or bronze aerial lines with 9 in. or 12 in. spacing between the wires the inductance is 3 to 4 mH. per mile, which has a very beneficial effect upon the attenuation constant.

Leakance of Aerial Lines. The insulation resistance of aerial lines varies, according to weather conditions, from several megohms per mile in dry weather to several hundred thousands of ohms per mile in wet weather. The B.P.O. requires its aerial lines to be maintained to a minimum figure of 200 000 ohms per mile, except for lines in special localities where such conditions as proximity to the sea adversely affect the insulation.

The above figures apply to measurements made by direct current methods which are normally used in maintenance work. The leakance at telephone frequencies is, however, considerably greater than with direct current. For aerial circuits it increases approximately directly as the frequency and at 800 per sec. it is probably from 10 to 100 times the direct current leakance.

Capacitance of Aerial Lines. The following formula gives the capacitance of a loop circuit when the effect of neighbouring wires and the earth can be neglected.

$$C = \frac{0 \cdot 194}{\log_{10} (2D/d)} \, \mu\text{F. per mile} \quad . \quad . \quad (46)$$

In practice, however, the effect of the earth and the neighbouring conductors cannot be neglected, and it is therefore impossible to state with any degree of accuracy the capacitances of aerial lines.

Attenuation and Characteristic Impedance of Aerial Lines. It is difficult to obtain the attenuations and characteristic

impedances of aerial lines from theoretical considerations, as the primary constants of leakance and capacitance cannot be stated with any degree of accuracy, and in the case of iron wire the effective resistance and inductance are also difficult to find.

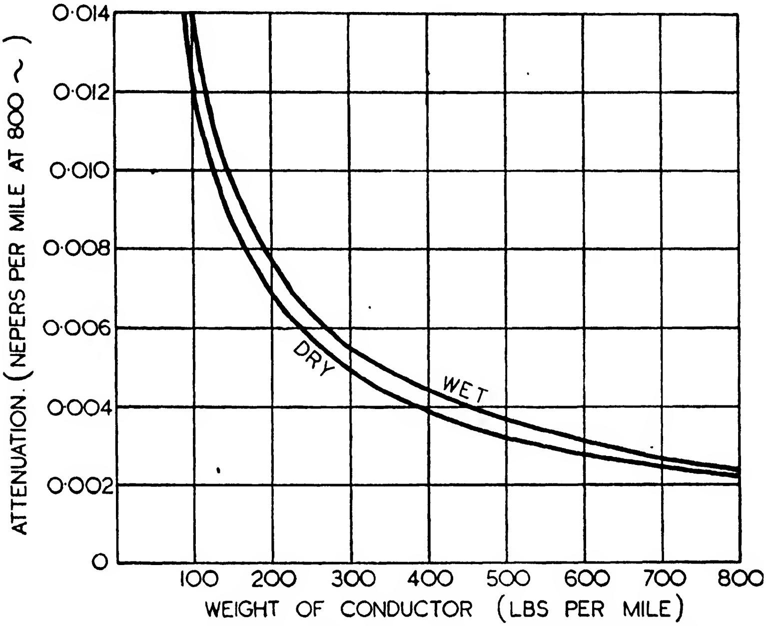


FIG. 288. ATTENUATION OF AERIAL LINES UNDER WET AND DRY CONDITIONS

If calculation is resorted to, however, it is best done from the following arrangement of the formulae—

$$P = \sqrt{(ZA)}\ \underline{/\tfrac{1}{2}(\phi_1 + \phi_2)} \qquad (47)$$

where

$$Z = \sqrt{(R^2 + \omega^2 L^2)} = R \sec \phi_1$$

$$A = \sqrt{(G^2 + \omega^2 C^2)} = G \sec \phi_2.$$

$$\tan \phi_1 = \omega L/R.$$

$$\tan \phi_2 = \omega C/G.$$

Then

$$\beta = \sqrt{(ZA)} \,.\, \cos \tfrac{1}{2}(\phi_1 + \phi_2). \qquad (48)$$

$$\alpha = \sqrt{(ZA)} \sin \tfrac{1}{2}(\phi_1 + \phi_2) \qquad (49)$$

and

$$Z_o = \sqrt{(Z/A)}\ \underline{/\tfrac{1}{2}(\phi_1 - \phi_2)} \qquad (50)$$

characteristic impedances of the various classes of aerial line used by the British Post Office. The attenuation of an aerial line may rise about 10 per cent in wet weather due to the increase in leakance.

TABLE 2

Transmission Constants of Aerial Lines

	Weight per mile (lb.)	Loop Resistance per mile (ohms)	Decibels per mile	P	Z_0
Bronze	40	91	0·33	0·0593 /50·7°	1 581 \37·7
	70	52	0·23	0·0473 /55·2°	1 197 \33·3
	150	24·3	0·14	0·0359 /63·2°	855 \25·5
Cadmium copper	40	52	0·22	0·0459 /55·7°	1 295 \33·2
	70	30	0·15	0·0380 /62·7°	963 \26·9
Hard-drawn copper	100	17·7	0·105	0·0326 /68·3°	804 \20·3
	150	11·8	0·076	0·0305 /73·4°	725 \15·4
	200	8·4	0·060	0·0296 /76·5°	687 \12·1
	300	5·88	0·042	0·0289 /80·3°	647 \8·4
	400	4·4	0·034	0·0286 /82·2°	621 \6·5
	600	2·93	0·024	0·0284 /84·4°	592 \4·4
Iron . . .	400	24	0·22	0·065 /67°	1 300 \22°

The attenuation of aerial lines does not vary very greatly with frequency. The figures given in Table 2 apply to a frequency of 800 per sec.; below 300 per sec., however, the attenuation falls rapidly until a value of $\beta = \sqrt{(RG)}$ is reached at zero frequency. The general form of the attenuation frequency curve is given in Fig. 288 for wet and dry weather conditions.

The characteristic impedance is also reasonably constant over the telephone frequency range. Fig. 289 shows the effective resistance and reactance figures for a 400-lb. copper aerial circuit.

Cable Circuits. Inland cables are of the air-spaced paper-core types, and the great advantage of the air-spaced cable from the

electrical point of view is its low capacitance, derived from the fact that the dielectric is mainly air; the paper and string serving to space the wires.

High conductivity annealed copper is used for cable conductors having an ohm-mile constant of 860·9 at 60° F., and a temperature coefficient of 0·00222 relative to its conductivity at 60° F. As with aerial conductors, cable conductors are designated by their weight per mile. In working out the actual resistance per mile of cable circuit, however, allowance must be made for the increase of length caused by the twinning and

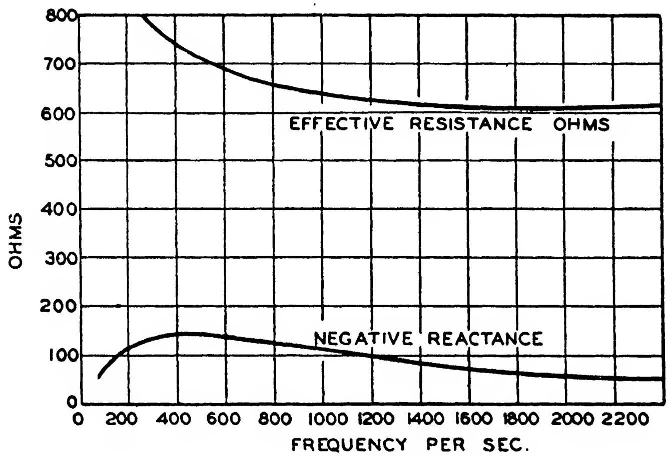


FIG. 289. IMPEDANCE OF 400 LB. COPPER AERIAL LINE

quadding of the conductors and the rotation of the conductors in the layers. For a large diameter cable the difference between wires in the centre and outer layers will be about 2·0 per cent, which gives a resistance constant of

$$\frac{1754{\cdot}4}{\text{weight}} \text{ ohms per mile of cable (loop.)}$$

The seasonal variation of direct current resistance due to temperature changes is probably about 5 per cent for underground cables laid in ducts, indicating a temperature range of about 20° F.

The mutual capacitance of paper-core cable pairs depends upon the spacing of the conductors: the greater the space occupied per pair, the less will be the wire to wire capacitance.

Since a larger diameter cable involves a larger cost for lead sheathing and duct space, it will be seen that in the electrical design of a cable a compromise must be made between circuit efficiency and various economic factors. The values of mutual capacitance for the multiple-twin and star-quad types of cable used by the British Post Office are given below—

Cable	Mutual Capacitance (μF. per mile)	Ratio : side/phantom
Multiple-twin	0·062	1 : 1·62
Star-Quad, 10 lb.	0·072	1 : 2·6
,, ,, 20 lb. and over	0·066	

The self-inductance of cable circuits is very much lower than that of aerial lines due to the much closer spacing of the wires. It is usual to allow 1 mH. per mile for calculation purposes for all types of cable.

The insulation resistance of modern cables often reaches the extremely high figure of 30 000–40 000 MΩ. per mile. The minimum insulation resistance required by the British Post Office is 10 000 MΩ. per mile.

The leakance is of course much greater than the figure indicated by the direct current insulation tests, due to the dielectric hysteresis, but even so it is extremely small at ordinary telephone frequencies. In calculating the attenuation constant of an unloaded cable circuit, neglecting the leakance does not involve an error greater than about 0·2 per cent.

In the case of loaded lines the effect of the small leakance is more marked as will be shown later. In factory testing of cables, measurements are made of the *dielectric constant* G/C, by means of an a.c. bridge. For good air-spaced paper-core cables values of 15 to 20 are obtained for G/C at a frequency of 800 per sec., indicating a leakance of about 1 micro-mho per loop mile. This value is sometimes used for G in calculations of attenuation.

Attenuation and Characteristic Impedance of Cable Circuits. When the inductance and leakance are negligible then formulae (23) and (24), Chapter XIV, are simplified to

$$\left.\begin{aligned}\beta &= \sqrt{(\omega CR/2)}\\ \alpha &= \sqrt{(\omega CR/2)}\end{aligned}\right\} \quad . \quad . \quad . \quad (51)$$

Also the characteristic impedance becomes

$$Z_o = \sqrt{(R/j\omega C)} = \sqrt{(R/\omega C)}\,\overline{/j^{\frac{1}{2}}}$$

Now since j represents a rotation of 90°, $j^{\frac{1}{2}}$ must represent an angle of 45° and

$$Z_o = \sqrt{(R/\omega C)}\,\overline{/45^\circ} \qquad (52)$$

If the leakance only is neglected then

$$\left.\begin{aligned}\beta &= \sqrt{\{\tfrac{1}{2}\omega C[\sqrt{(R^2 + \omega^2 L^2)} - \omega L]\}} \\ \alpha &= \sqrt{\{\tfrac{1}{2}\omega C[\sqrt{(R^2 + \omega^2 L^2)} + \omega L]\}}\end{aligned}\right\} \qquad (53)$$

$$Z_o = \sqrt[4]{\frac{R^2 + \omega^2 L^2}{\omega^2 C^2}}\,\overline{\Big/ 45^\circ - \tfrac{1}{2}\tan^{-1}\frac{\omega L}{R}} \qquad (54)$$

The inductance thus decreases the attenuation constant and increases the wavelength constant whilst the characteristic impedance is increased and its angle reduced to something less than 45°.

The characteristics of unloaded cable circuits at 800 per sec. are given in Table 3. An inductance of 1 mH. per mile has been assumed in calculating the characteristics.

TABLE 3

CONSTANTS OF CABLE CIRCUITS AT FREQUENCIES OF 800 PER SEC.
(Unloaded side circuits)

Type	Weight of Conductor (lb. per m.)	Loop Resistance (ohms)	Decibels per mile	P	Z_o
Star-quad .	6½	270	1·92	0·312 /45·0	866 \45
	10	176	1·53	0·252 /45·8	699 \44·2
	*20	88	1·02	0·171 /46·7	516 \43·3
	*40	44	0·70	0·121 /48·3	366 \41·7
	*70	25	0·50	0·092 /50·6	283 \39·4
Multiple-twin types only	100	17·6	0·40	0·075 /52·6	243 \37·4
	150	11·7	0·30	0·063 /56·5	202 \33·5
	200	8·8	0·25	0·056 /59·8	180 \30·2

* M.T. types: 3 per cent lower attenuation.

Unloaded phantom circuits are sometimes used on multiple-twin types of cable, the attenuation being about 10 per cent

lower than that of side circuits. This can be shown as follows. For the side circuit, attenuation is given by

$$\beta \doteq \sqrt{(R\omega C/2)}$$

and using side-circuit values for R and C the phantom attenuation is

$$\beta \doteq \sqrt{[(\tfrac{1}{2}R \,.\, \omega C \,.\, 1{\cdot}6)/2]} = 0{\cdot}89\sqrt{(R\omega C/2)}.$$

In the case of star-quad type cables it is not usual to use the phantom circuits for any purpose other than signalling as the degree of capacitance unbalance would give rise to excessive cross-talk. If they were used, however, the attenuation would be greater than that of the side circuits in the ratio $\sqrt{2{\cdot}6} : \sqrt{2}$ approximately, or about 14 per cent. Table 4 gives the calculated characteristics of phantom circuits on some multiple-twin type cables.

TABLE 4

Constants of Cable Circuits at Frequencies of 800 per sec.
(Unloaded Phantom Circuits)

Type	Weight of Conductor (lb. per mile)	Loop Resistance (ohms per mile)	Decibels per mile	P per mile	Z_0
Multiple-twin types only	20	44	0·89	$0{\cdot}149 \angle 46{\cdot}7$	$296 \backslash\overline{43{\cdot}3}$
	40	22	0·61	$0{\cdot}106 \angle 48{\cdot}3$	$210 \backslash\overline{41{\cdot}7}$
	70	12·5	0·44	$0{\cdot}080 \angle 50{\cdot}6$	$159 \backslash\overline{39{\cdot}4}$
	100	8·8	0·36	$0{\cdot}068 \angle 52{\cdot}6$	$135 \backslash\overline{37{\cdot}4}$

Distortion on Unloaded Cable Circuits. It will be seen from equation (51) that the attenuation of an unloaded cable circuit increases in proportion to the square-root of the frequency. This is exactly true when there is no inductance, and approximately true when the inductance is small. The addition of uniformly distributed inductances, however, reduces the value of the attenuation at all frequencies. Fig. 290 shows curves of attenuation against frequency calculated from equation (53) for 0, 2, 5, and 10 mH. per mile.

Equation (51) shows also that the wavelength constant of an unloaded cable circuit increases in proportion to the square-root of the frequency as does the attenuation. Now the velocity of

propagation of a speech wave is given from equation (20), Chapter XIV, as

$$S = \omega/\alpha.$$

Substituting from (51) therefore gives

$$S = \sqrt{(2\omega/RC)}$$

showing that the velocity is also proportional to the square-root of the frequency.

On unloaded cable, therefore, speech waves are subject to two serious forms of distortion—

(*a*) The high frequencies are attenuated to a greater degree than the lower frequencies giving attenuation distortion.

(*b*) The high frequencies travel faster than the lower frequencies giving phase distortion (American term, *delay distortion*). The first form of distortion is the more serious.

The High Attenuation of Cable Circuits. It is not possible to carry on a satisfactory telephone conversation if the total circuit attenuation between the telephones is much greater than 30 db., and even with this loss the telephone must not be situated where there is considerable room noise. Any attenuation and phase distortion will further reduce the efficiency of the circuit.

The lengths of the various classes of circuit required to give an attenuation of 30 db. are shown below. The figures are not intended to indicate the limiting distances but are given merely as a rough comparison of circuit efficiency.

Cable Circuits		Aerial Circuits	
6½ lb. P.C.Q.T.	15·5 miles	40 lb. Bronze	91 miles
10 ,, ,,	19·5 ,,	70 ,, ,,	130 ,,
20 ,, ,,	29·5 ,,	100 ,, Copper	286 ,,
40 ,, ,,	43·0 ,,	150 ,, ,,	395 ,,
70 ,, ,,	59·5 ,,	200 ,, ,,	500 ,,
100 ,, P.C.M.T.	76·0 ,,	300 ,, ,,	715 ,,
200 ,, ,,	123 ,,	400 ,, ,,	884 ,,

It will be seen from the above figures that aerial circuits are many times more efficient than cable circuits, and in addition they do not give rise to as much distortion. On a 70-lb. cable circuit 60 miles in length, having an attenuation of 30 db. at 800 per sec. frequency, the attenuation distortion will be

such that at 2 000 per sec. frequency the attenuation will be over 47 db.

The inefficiency of cable circuits is due to the high capacitance between the wires, and any improvement which might be affected by reducing this capacitance would be limited and costly. A great improvement can, however, be affected by increasing the inductance of the wires; the process being known as *loading*. Loading also reduces the attenuation and phase distortion as will be shown later.

The Theory of Loading. The graphs in Fig. 290 calculated from equation (53) show that an increase in the inductance of a

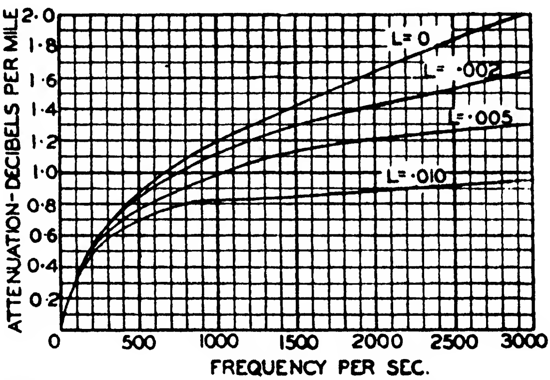


FIG. 290. ATTENUATION OF 20 LB. CABLE CIRCUITS WITH SMALL VALUES OF INDUCTANCE
Calculated from equation (53).

line reduces the attenuation. It is also evident from equation (53) that the wavelength constant is increased at the same time. These effects can perhaps be understood most clearly by studying the propagation constant

$$P = \sqrt{[(R + j\omega L)(G + j\omega C)]}.$$

The polar form of this equation is

$$P = \sqrt{(R^2 + \omega^2 L^2)(G^2 + \omega^2 C^2)} \,/\tfrac{1}{2}(\phi_1 + \phi_2). \quad (55)$$

Where
$$\phi_1 = \tan^{-1}(\omega L/R);$$
$$\phi_2 = \tan^{-1}(\omega C/G).$$

It is obvious that any increase of L will increase the value of P and its angle will also be increased. Fig. 291 shows the propagation constants drawn as vectors calculated from the

above, neglecting G, for a 20-lb. cable pair with (*a*) no inductance; (*b*) 10 mH. per mile; (*c*) 20 mH. per mile; frequency 800 per sec.

Fig. 291 shows clearly that although the addition of inductance increases the propagation constant, the angle is so increased that its real part β is actually decreased at the expense of the unreal part α.

The increase in α means a reduced velocity for the wave, which is evident from equation (20), Chapter XIV, $S = \omega/\alpha$.

The effect of loading is therefore to reduce the attenuation and to slow down the velocity of propagation.

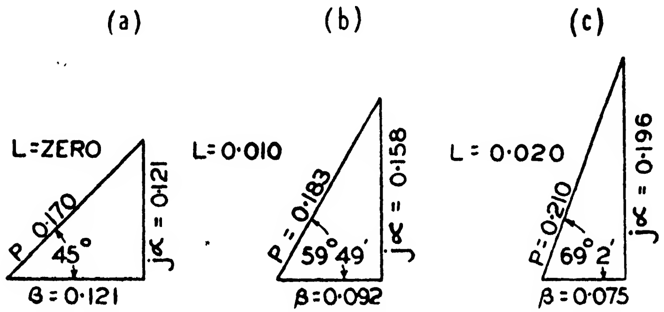


FIG. 291. EFFECT OF LOADING ON PROPAGATION CONSTANT

The Attenuation of Loaded Lines. It is convenient at this stage in investigating the properties of loaded lines to assume that the inductance is uniformly distributed along the line.

If the inductance is so increased that ωL is large compared with R, then equation (53) can be simplified as follows—

$$\beta^2 = \tfrac{1}{2}\omega C[\sqrt{(R^2 + \omega^2 L^2)} - \omega L]$$
$$= \tfrac{1}{2}\omega^2 CL[(1 + R^2/\omega^2 L^2)^{\frac{1}{2}} - 1].$$

Since $R^2/\omega^2 L^2$ is small, the quantity in the inner bracket can be written by the binomial approximation, $(1 + \delta)^n = 1 + n\delta$.

$$(1 + R^2/\omega^2 L^2)^{\frac{1}{2}} = 1 + R^2/2\omega^2 L^2.$$

Substituting, $\beta^2 = \tfrac{1}{2}\omega^2 CL\,(1 + R^2/2\omega^2 L^2 - 1)$

$$= R^2 C/4L,$$

or $$\beta = \tfrac{1}{2}R\sqrt{(C/L)} \quad . \quad . \quad . \quad . \quad . \quad (56)$$

By this formula the attenuation is independent of the frequency and there is therefore no amplitude distortion. This

is true except at very low frequencies. The condition for no phase distortion is that α should be directly proportional to ω. So long as ωL is large compared with R, then equation (53) gives $\alpha = \omega\sqrt{(LC)}$ which is a distortionless condition and holds good down to fairly low frequencies on ordinary loaded lines.

It has been stated that for unloaded cable circuits the normal leakance of about 1 micro-mho per mile has a negligible effect upon the attenuation constant β, and formula (53) has also been developed upon this assumption. When, however, the amount of inductance added to the line is large the leakance becomes much more important. In taking account of G it can, however, be assumed that it is small compared with ωC.

Adopting the same method as was used to obtain equation (56) it will be found that equation (23), Chapter XIV—

$$\beta = \sqrt{\tfrac{1}{2}\{\sqrt{[(R^2 + \omega^2L^2)(G^2 + \omega^2C^2)]} + (RG - \omega^2LC)\}}$$

can be simplified to

$$\beta = \tfrac{1}{2}R\sqrt{(C/L)} + \tfrac{1}{2}G\sqrt{(L/C)} \quad . \quad . \quad (57)$$

The first term is the same as equation (56) and is termed the *resistance damping*. The second term is called the *leakance damping*.

Equation (57) can also be written in the following convenient forms—

$$\beta = \tfrac{1}{2}\sqrt{(C/L)}\,.\,[R + (G/C)L]$$

and

$$\beta = \tfrac{1}{2}\sqrt{(LC)}\,.\,(R/L + G/C),$$

which show clearly the effect of the leakance damping as the inductance is increased.

The characteristic impedance can also be simplified. Equation (12), Chapter XIV,

$$Z_o = \sqrt{\left[\frac{R + j\omega L}{G + j\omega C}\right]}$$

becomes

$$Z_o = \sqrt{(L/C)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (58)$$

which is non-reactive and independent of frequency.

Equations 57 and 58 allow the characteristics of coil-loaded lines to be readily calculated. They also apply with reasonable accuracy to aerial lines with heavy conductors, but in this case the primary constants are difficult to obtain, as has already been pointed out.

The Distortionless Condition. In Fig. 292 attenuation has been plotted against inductance from equation (57) and it will be seen that there is a minimum value for β, and that any

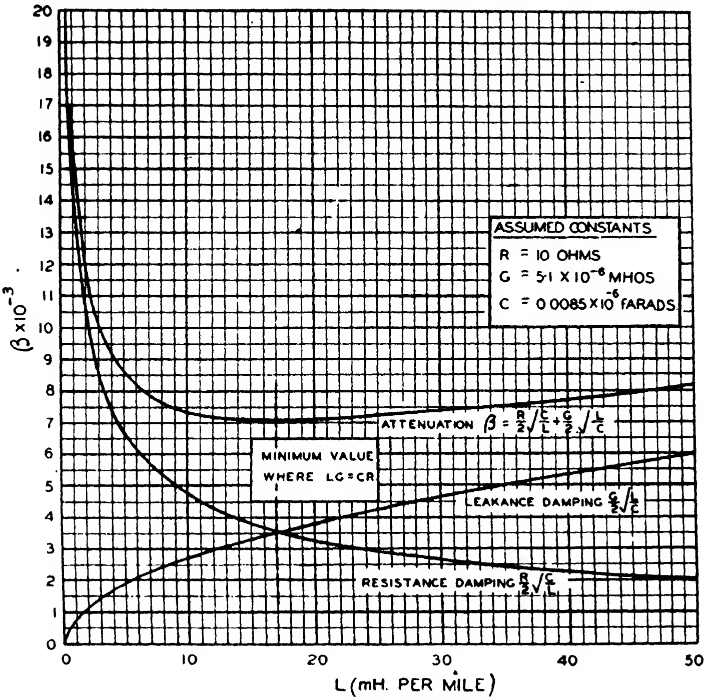


FIG. 292. RESISTANCE AND LEAKAGE DAMPING

further increase in inductance will produce an increase in attenuation.

The condition for minimum attenuation can be found as follows. Rewrite (57)

$$\beta = R/2Z_0 + GZ_0/2 \quad . \quad . \quad . \quad (59)$$

Differentiating (59)

$$d\beta/dZ_0 = -R/2Z_0^2 + G/2.$$

Equating to zero

$$R/2Z_0^2 = G/2$$

or

$$Z_0^2 = R/G = L/C.$$

The required condition is thus

$$LG = CR \quad . \quad . \quad . \quad . \quad . \quad (60)$$

That this must be a distortionless condition at all frequencies can be seen by considering the characteristic impedance in full, equation (12), Chapter XIV.

$$Z_o = \sqrt{\left[\frac{R + j\omega L}{G + j\omega C}\right]}$$

$$= \sqrt[4]{\left[\frac{R^2 + \omega^2 L^2}{G^2 + \omega^2 C^2} \underline{/\phi_1 - \phi_2}\right]}$$

where $\phi_1 = \tan^{-1}(\omega L/R)$ and $\phi_2 = \tan^{-1}(\omega C/G)$.

If $\phi_1 = \phi_2$ Z_o is non-reactive

$$\omega L/R = \omega C/G \text{ or } LG = CR.$$

Since Z_o is not reactive, any section of such a line must absorb power independently of frequency and must pass on power independently of frequency.

Given the distortionless condition it is easily shown that

$$\left.\begin{aligned} \beta &= \sqrt{(RG)} \\ \alpha &= \omega\sqrt{(LC)} \\ Z_o &= \sqrt{(R/G)} = \sqrt{(L/C)} \end{aligned}\right\} \quad . \quad . \quad (61)$$

The last of these will be developed to show the method.

$$Z_o = \sqrt[4]{\left[\frac{R^2 + \omega^2 L^2}{G^2 + \omega^2 C^2}\right]}$$

$$= \sqrt{\frac{(1 + \omega^2 L^2/R^2)R^2}{(1 + \omega^2 C^2/G^2)G^2}}.$$

Since $\omega L/R = \omega C/G$, $Z_o = \sqrt{(R/G)}$.

The rest of (61) is found similarly. It is seen that β is independent of frequency and since α is proportional to ω, the velocity must be independent of frequency also. Thus there is no attenuation distortion or phase distortion.

With unloaded telephone cables LG is always very much smaller than CR; hence the reason for inductance loading. The distortionless condition could be approached by increasing the leakance G, but such a method would have the disadvantage of increasing the attenuation and would thus be counter to the chief reason for loading. Fig. 292 makes this clear. It is not possible for many practical reasons to load circuits to the distortionless condition. For example, standard cable would

require over four henries per mile and it must not be forgotten that the additional inductance will involve additional copper loss, hysteresis loss and eddy-current loss.

Methods of Loading. The condition for a distortionless line which has just been given was first shown by Oliver Heaviside in 1885. Heaviside himself suggested a number of ways by which a useful approximation to the distortionless condition might possibly be effected: including the idea of series inductance coils spaced at regular intervals along the line. Other suggestions soon followed, including one by Professor S. P. Thompson for inductance coils at regular intervals along the line and connected across the circuit.

For many years these ideas for the improvement of the efficiency of long telephone lines were ignored by practical engineers. In 1901 Prof. M. I. Pupin published papers showing mathematically how a telephone line loaded with series inductance coils at regular intervals would be approximately equivalent to the same cable with the same amount of inductance uniformly distributed, provided that the spacing of the coils did not exceed certain limits. He showed also how the required spacing for the coils and the degree of approximation to the uniform line could be determined.

G. H. Campbell also worked out the same problem about the same time as Prof. Pupin, who was, however, able to complete his work before Campbell and so obtained the patents.

Coil Loading. *Pupin loading* or *coil loading* has since become one of the most important aspects of telephony. On modern cables the coils have inductances of from 16 to 200 mH. and are spaced at 1 000, 2 000, or 4 000 yd. according to the characteristics required.

The coils are wound on ring cores made of finely divided iron of high permeability mixed with a binding material, mostly shellac, and compressed at about 50 tons per in.^{2} into the required toroidal shape. This construction gives very low hysteresis and eddy-current loss, and good magnetic stability. Originally, iron wire cores were used, but the coils had greater iron losses than the modern dust core coils and their inductance was far less stable. Half the inductance is inserted in the A-wire and half in the B-wire, each line winding being made up of two windings arranged as shown in Fig. 293.

The phantom circuits can also be loaded, by inserting separate coils with windings arranged as shown in Fig. 294.

It is possible to load the phantoms without separate coils

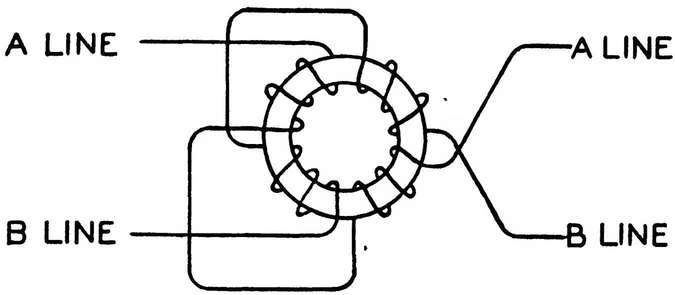


FIG. 293. LOADING COIL WINDINGS

by putting additional windings on the side circuit coils, but the method is not used in practice.

Each complete coil is enclosed in a metal case to shield it from the effects of leakage flux from adjacent coils, which would give rise to slight cross-talk.

The inductance given by loading coils must be obtained by

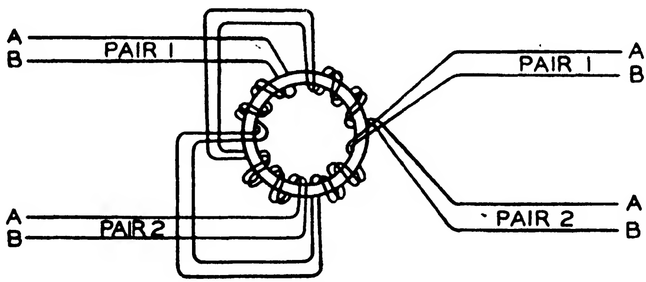


FIG. 294. LOADING OF PHANTOM CIRCUITS

as small an increase in resistance as possible, compatible with reasonable size of coil and cost. The maximum resistance limits laid down by the British Post Office for the standard types of coils now used in this country are given in Table 4, for three grades of coils.

Grade 1 is used for music circuits, carrier circuits and international circuits. Grade 2 is used for important trunk circuits, and Grade 3 is used for minor trunk, toll, and junction circuits.

TABLE 4

EFFECTIVE RESISTANCE LIMITS FOR LOADING COILS
(Used by the British Post Office)

Inductance (mH.)	Grade 1	Grade 2	Grade 3
Side Circuits			
176		10·0	
136		7·8	11·2
120	6·3	7·0	10·0
88	4·7	5·2	7·9
68		4·2	
60	3·4	3·8	5·8
44	2·7	3·0	4·8
			(30) 4·0
22	1·6	1·8	3·4
11	1·1	1·3	
Side and Phantom Circuits			
120 + 40	9·8	10·8	
88 + 32	7·5	8·3	
60 + 20	5·6	6·2	
44 + 24	5·2	5·8	
44 + 16	4·7	5·2	
22 + 12	3·1	3·4	
Programme Circuits			
22	4·0		
16	3·0		
11	2·2		
8	1·9		

Note. Side and Side + phantom limits at 800 per sec. frequency.
Programme limits at 1 800 per sec. frequency.

Very narrow limits are also laid down for resistance unbalance, capacitance unbalance, and inductance unbalance. Coils are also tested for magnetic stability and hysteresis factor.

Continuous Loading. Another type of loading known as *continuous loading* is used for submarine cables and in certain special circumstances for inland cables. It was first introduced by the Danish telephone engineer, Mr. C. E. Krarup, and is sometimes known as '*Krarup*' *loading*. By this method an increase in inductance is obtained by wrapping the conductors with fine iron wire, of from 5 to 10 mils diameter. No insulation is placed between the conductor and the loading wire. Usually only about 10–20 mH. per naut is added, but it is possible by using a loading wire of one of the high permeability alloys to increase this figure many times, as has been done on some of

the modern ocean telegraph cables. This method has the advantage of loading the phantom circuits at the same time, but of course since two wires are in parallel for a phantom circuit, only half as much inductance is added to the phantom circuits per naut as to the side circuits.

Due to the uniform characteristics produced by continuous loading, it can be applied to short lengths of cable such as are often required to be inserted in aerial lines at power line crossings, etc.; whereas with coil loading at least three coils are necessary before anything like uniform characteristics are obtained, and before the formulæ given in the preceding sections can be applied.

Continuous loading has certain advantages where sea cables are concerned, connected mainly with the construction, laying and repair of such cables. These will be dealt with in Chapter XIX on submarine cables. Electrically, however, continuous loading is in many ways inferior to coil loading for the following reasons—

(*a*) The amount of inductance which can be added is small.

(*b*) The addition of the iron wire increases the mutual capacitance of the conductors considerably, and thereby reduces the effectiveness of the loading.

(*c*) Generally the hysteresis and the eddy current losses are greater than with coil loading, and therefore give rise to more distortion since these factors increase in direct proportion to the frequency, and to the square of the frequency respectively.

(*d*) Continuous loading is much more costly than coil loading and cannot be applied to existing cables.

Constants of Coil-loaded Lines at 800 per sec. Frequency. Coil-loaded lines are designed to be equivalent to smooth lines at average speech frequencies. The spacing is such that there are at least ten coils per wavelength. Attenuation and impedance calculations for frequencies of 800 per sec. can therefore be made with reasonable accuracy from the following equations.

$$\left.\begin{aligned} \beta &= \tfrac{1}{2}R\sqrt{(C/L)} + \tfrac{1}{2}G\sqrt{(L/C)} \\ \alpha &= \omega\sqrt{(LC)} \\ Z_o &= \sqrt[4]{\frac{R^2 + \omega^2 L^2}{\omega^2 C^2}} \,\Big|\, \frac{90^\circ - \tan^{-1}(\omega L/R)}{2} \end{aligned}\right\} \quad . \quad (62)$$

β can be written

$$\beta = \tfrac{1}{2}\sqrt{(C/L)}\,.\,(R + (G/C)L).$$

Taking a value of 20 for G/C;

$$\beta = \tfrac{1}{2}\sqrt{(C/L)}\,.\,(R + 20L). \tag{63}$$

It must not be forgotten that seasonal temperature changes affect the resistance by about 5 per cent and a similar percentage variation will take place in the attenuation since in equation (63) $20L$ is small compared with R.

Transmission constants at frequencies of 800 per sec. of the main types of loaded cables used in this country are given in Table 5, calculated from nominal primary constants. The

TABLE 5

TRANSMISSION CONSTANTS OF LOADED CIRCUITS AT FREQUENCIES OF 800 PER SEC.

Inductance per Coil (mH.)	Spacing in miles	Attenuation in decibels per mile			Cut-off Frequency (cyc.)	Characteristic Impedance	Wave-length Constant
		20 lb.	40 lb.	70 lb.			
Side Circuits							
253	1·136	0·252	0·156	0·112	2 320	1 858 \1·5°	0·604
177	1·136	0·288	0·165	0·113	2 770	1 556 \2·0°	0·505
136	1·136	0·315	0·176	0·117	3 170	1 367 \2·0°	0·444
120	1·136	0·33	0·179		3 400	1 300 \2·5°	0·414
88	1·136	0·372	0·201	0·127	3 920	1 110 \3·5°	0·360
44	1·136	0·496	0·262	0·158	5 570	793 \6·5°	2·256
22	1·136		0·36*		7 800	572 \12·3°	0·182
16	1·136		0·413*		9 120	505 \16·5°	0·155
177	1·6	0·326			2 340	1 313 \2·6°	0·426
136	2·6	0·44	0·234	0·144	2 090	913 \5·0°	0·295
Phantom Circuits							
155	1·136	0·195	0·119	0·086	2 520	1 241 \1·2°	0·559
107	1·136	0·222	0·127	0·087	3 040	1 030 \1·6°	0·463
82	1·136	0·232	0·137	0·091	3 480	904 \2·0°	0·406
54	1·136	0·282	0·153	0·098	4 280	737 \2·8°	0·331
25	1·136	0·386	0·203	0·123	6 300	511 \5·6°	0·229

* Not phantom loaded.

characteristic impedances and wavelength constants quoted apply particularly to the 40 lb. conductors, but no appreciable error is introduced by applying them to 20 lb. and 70 lb. conductors.

Fig. 295 shows circuit attenuation per mile plotted against loading in millihenries per mile. It will be seen that loading

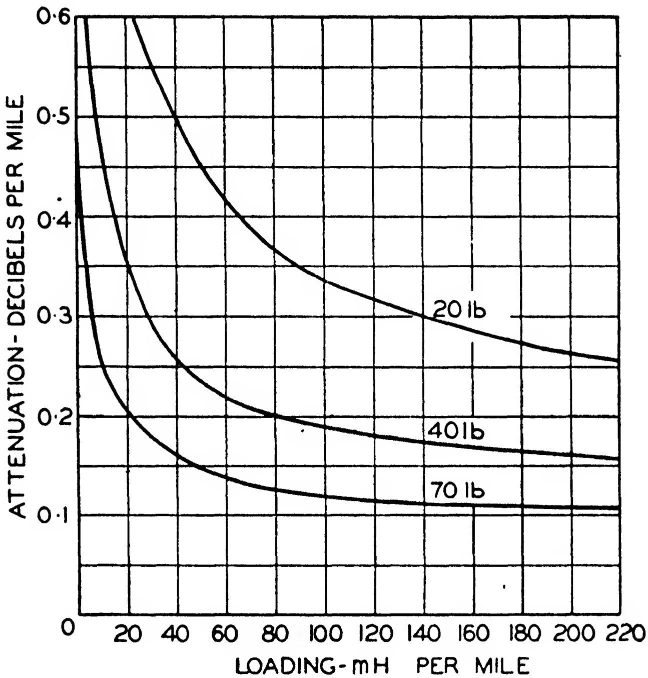


FIG. 295. SIDE CIRCUIT ATTENUATION
Decibels per mile at 800 cycles per sec.

above about 100 mH. per mile must be very expensive considering the smallness of the improvement obtained by further loading.

Some constants for continuously loaded cables are given in the chapter on submarine cables.

Coil-loaded Lines at the Higher Speech Frequencies. It has been stated that coil-loaded lines are designed to be equivalent to smooth lines at the most important speech frequencies. From eight to twenty coils per wavelength at frequencies of 800 per sec. are inserted. When the frequency is increased,

however, the number of coils per wavelength decreases, the degree of approximation to a uniform line decreases also, and the attenuation becomes progressively greater than that of the nominally equivalent smooth line. When the frequency is increased beyond the value where there are less than about four coils per wavelength, the attenuation increases rapidly—so much so that the line in effect refuses to transmit all frequencies above what is known as the *cut-off* frequency—at the frequency giving two coils per wavelength. If the same inductance were regarded as being added uniformly there would be π coils per wavelength at this frequency, and of course no sharp rise of attenuation. Some cut-off frequencies have already been given in Table 5 for the more common types of loaded lines.

The cut-off effect is a serious disadvantage of coil loading, and it is therefore an important consideration in the design of loaded cables. The effective transmitted frequency band is regarded as 0·7 or 0·8 of the theoretical cut-off frequency. It has been agreed by the C.C.I.F. that for international circuits up to 300 km. in length, a frequency band of from 300 to 2 400 per sec. should be transmitted, and for international circuits over 300 km. in length a frequency band of from 300 to 2 600 per sec. should be transmitted. Circuits to be used for radio transmissions should effectively transmit from 50 to 6 400 per sec. A frequency is effectively transmitted if the attenuation at that frequency does not exceed the attenuation at 800 per sec. by more than 1 néper.

Cut-off Frequency. The phenomenon of cut-off is due to resonance between the lumped inductances of the loading coils and the capacitance of the line between the coils. This resonance prevents energy from progressing along the line in the form of a wave motion as occurs in the case of a uniform line and which has been described in Chapter XIV. It will be shown in Chapter XVI on filters that the cut-off frequency is the resonant frequency of half the inductance of one loading coil, and half the capacitance of one loading coil section.

A coil-loaded wire can be represented by a series of 'T' or 'Π' networks as shown in Fig. 296. The length of cable between loading coils can be represented sufficiently accurately by a nominal 'T' section, and the natural inductance of the cable

has been neglected by comparison with the loading coil inductance.

It will be seen that for a symmetrical arrangement and to

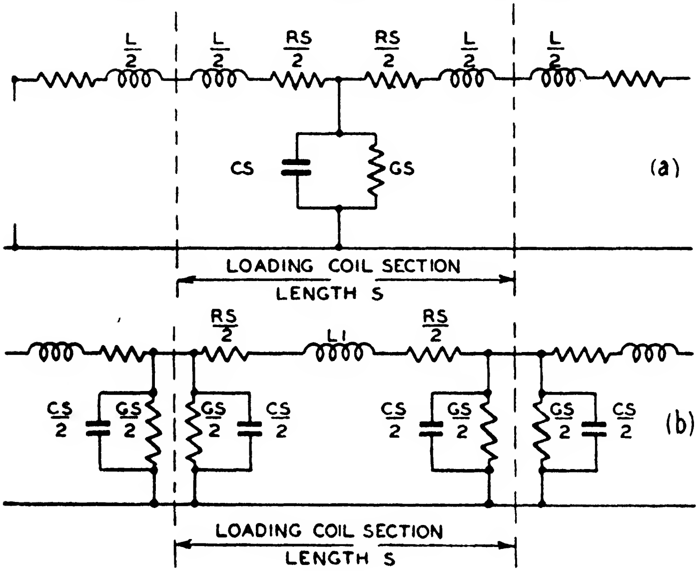


FIG. 296. NOMINAL 'T' AND 'π' NETWORKS OF A COIL-LOADED LINE

allow of interconnecting loaded cables without producing a serious irregularity, a loaded cable should be terminated with either a half-coil or a half-loading coil section and in practice

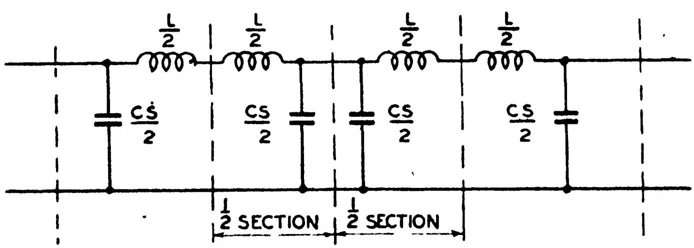


FIG. 297. NOMINAL HALF-SECTIONS OF A COIL-LOADED LINE

this is arranged as far as possible. The half-section termination is most usual for reasons of economy.

In considering the theoretical cut-off frequency, resistance and leakance can be neglected, and the networks as shown in Fig. 296 reduced to a series of half-sections arranged back to back, as in Fig. 297.

The resonant frequency ω_c of these half-sections is given by

$$\tfrac{1}{2}\omega_c L = 2/\omega_c C_s,$$

or

$$\left.\begin{aligned} \omega_c &= 2/\sqrt{(LC_s)}, \\ f_c &= 1/\pi\sqrt{(LC_s)}. \end{aligned}\right\} \quad . \quad . \quad (64)$$

and

If equation (64) is substituted in the formula for the attenuation of a loaded line the result is—

$$\begin{aligned} \beta &= \tfrac{1}{2}R\sqrt{(C_s/L)} \text{ per section} \\ &= \tfrac{1}{2}R\sqrt{(C/L_s)} \text{ per mile} \\ &= \tfrac{1}{4}RC\omega_c \quad \text{ per mile.} \end{aligned}$$

It follows therefore that for a given type of cable and a given loading coil spacing distance, the attenuation can only be

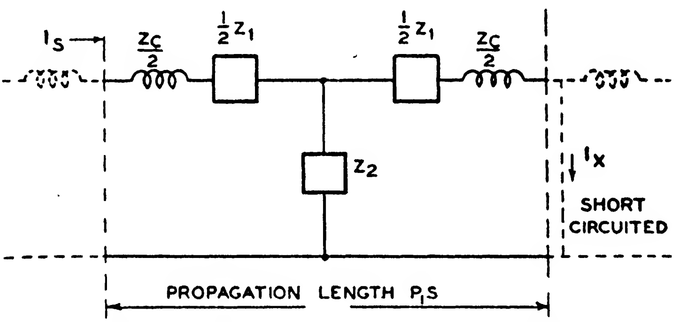


Fig. 298. Equivalent 'T' of Loading Coil Section

reduced at the expense of the frequency band transmitted, since β is proportional to ω_c.

Campbell's Formula. The propagation constant of a coil-loaded line is given fully by a formula which can be developed as follows.

Using P and Z_o for the unloaded lines;

P_1	for the loaded line;
Z_c	for loading coil impedance;
s	spacing between coils (in miles);

a single loading coil section is correctly represented by the network shown in Fig. 298, in which Z_1 and Z_2 are the elements of the equivalent network for the section of cable.

Let the distant end of the section be short circuited: then equation (37), Chapter XIV, can be applied.

$$i_s = i_x \cosh P_1 s.$$

Then $$\cosh P_1 s = i_s/i_x = (\tfrac{1}{2}Z_1 + Z_2 + \tfrac{1}{2}Z_c)/Z_2,$$
$$= 1 + Z_1/2Z_2 + Z_c/2Z_2 \quad . \quad . \quad . \quad (a)$$

Substituting again from equation (37), Chapter XIV, and from equation (32), Chapter XIV, (a) becomes

$$\cosh P_1 s = \cosh Ps + (Z_c/2Z_o) \sinh Ps \quad . \quad . \quad (65)$$

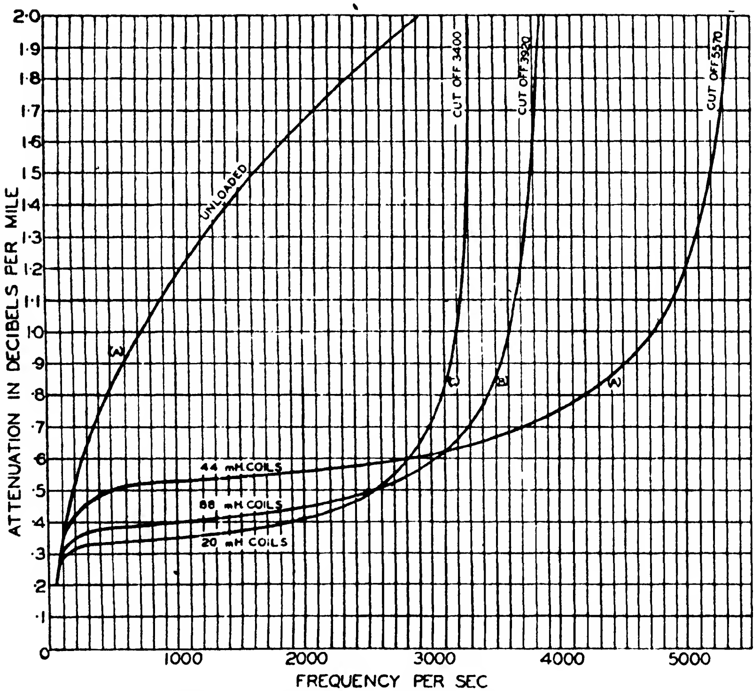


FIG. 299. ATTENUATION OF 40 LB. CABLE PAIRS, UNLOADED AND LOADED WITH COILS AT 2 000 YD.

This is Campbell's formula giving rigorously the propagation of the loaded line in terms of the propagation of the unloaded line and the loading coil impedance. Calculation from the formula is, however, laborious, and is rarely resorted to in practice.

Curves a, b, and c, Fig. 299, show the calculated attenuation-frequency characteristics of 20 lb. cable pairs loaded with 44, 88, and 120 mH. coils at 2 000 yd. spacing. A curve for unloaded pairs is also shown for comparison (curve d). The curves show clearly that the beneficial effects of loading as indicated by the smooth line formulae given in the preceding paragraphs are achieved by coil loading for frequencies up to those approaching the cut-off frequency.

CHAPTER XVI

WAVE FILTERS AND ATTENUATION EQUALIZERS

Wave Filters. Campbell's work on coil-loaded lines led him to the discovery of the idea of electric wave filters, i.e. electric networks capable of discriminating against certain bands of frequencies.

Wave filters are of four main classes, viz.—

(*a*) Low pass.
(*b*) High pass.
(*c*) Band pass.
(*d*) Band stop.

The simplest forms of these filters are shown in Fig. 300. It is seen that the simple low pass and high pass filters consist of series inductance and shunt capacitance and vice versa, whilst the band pass and band stop filters require tuned circuits for either or both of the series and shunt elements. In practice more complicated networks are often used in order to obtain better frequency discrimination and better impedance conditions. The theory of the simple forms of the low pass and high pass filters is given in the following sections. For more complicated sections the reader is referred to specialist books on the subject. (See Bibliography.)

General Theory. The theory of mid-series and mid-shunt networks has been given in Chapter XIV (pp. 345–7) and the following formulae were obtained—

$$\cosh \theta = 1 + Z_1/2Z_2.$$

$$Z_0 = \sqrt{[Z_1 Z_2 (1 + Z_1/4Z_2)]} \text{ mid-series.}$$

$$Z_0 = \sqrt{\frac{Z_1 Z_2}{1 + Z_1/4Z_2}} \text{ mid-shunt.}$$

In the case of ideal filters, i.e. filters without losses, in which Z_1 and Z_2 are pure reactances, the above formulae can be simplified. In this case $Z_1/2Z_2$ is non-complex, i.e. has a phase angle of 0° or 180°. Then for the low pass filter in Fig. 300—

$$Z_1/2Z_2 = -\tfrac{1}{2}\omega^2 LC = \tfrac{1}{2}\omega^2 LC\backslash\overline{180^\circ}.$$

For the high pass filter

$$Z_1/2Z_2 = -8/\omega^2 LC = 8/\omega^2 LC\backslash\overline{180^\circ}.$$

It can be noted also for the simple low pass and high pass filters of Fig. 300, that the product of the series and shunt

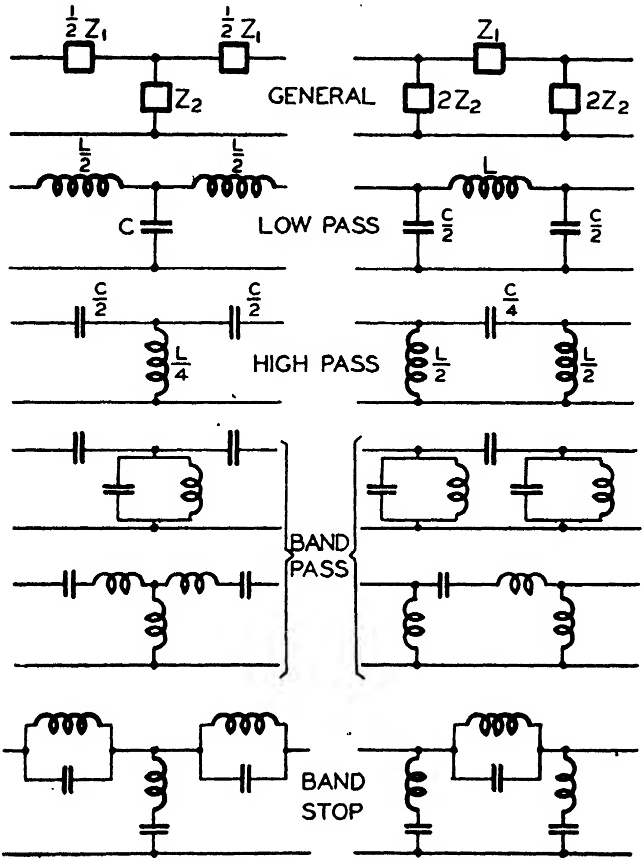


FIG. 300. MID-SERIES AND MID-SHUNT SECTION FILTERS

impedances is independent of frequency, or $Z_1Z_2 =$ constant. Such filters are termed *constant-k* filters.

Expansion of Cosh θ.

Now $\qquad \cosh\theta = \cosh(\beta + j\alpha) = 1 + Z_1/2Z_2.$

Expanding this, $\cosh\beta\cos\alpha + j\sinh\beta\sin\alpha = 1 + Z_1/2Z_2.$

Equating real and unreal parts for the case of an ideal filter,

$$\text{Cosh}\,\beta\cos\alpha = 1 + Z_1/2Z_2 \quad . \quad . \quad (a)$$

$$\text{Sinh}\,\beta\sin\alpha = 0 \quad . \quad . \quad . \quad . \quad (b)$$

The second of these, (b), can be true under two conditions, viz.—

$$\text{(i) Sinh}\,\beta = 0$$
$$\text{(ii) Sin}\ \alpha = 0$$

Pass Band.

Condition (i) gives $\beta = 0$, that is, no attenuation or a pass band condition. Then from (a)

$$\text{Cos}\ \alpha = 1 + Z_1/2Z_2.$$

Since $1 - \cos\alpha = 2\sin^2 \tfrac{1}{2}\alpha$,

$$\text{Sin}^2\ \tfrac{1}{2}\alpha = -\,Z_1/4Z_2 \qquad . \qquad . \qquad . \quad (66)$$

This is an expression for the phase shift in the pass band. Now $\sin^2 \tfrac{1}{2}\alpha$ can only vary between 0 and $+\ 1$, the limits of the pass band are thus

$$Z_1/4Z_2 = 0 \text{ and } Z_1/4Z_2 = -\ 1 \qquad . \qquad . \quad (67)$$

Attenuating Band.

Condition (ii) above gives $\alpha = m$ where $m\pi$ is any integer. Substituting in (a),

$$\pm\cosh\beta = 1 + Z_1/2Z_2.$$

Taking the negative sign and remembering that $(\cosh 2a - 1) = 2\cosh^2 a$

$$\cosh^2 \tfrac{1}{2}\beta = -\,Z_1/4Z_2 \qquad . \qquad . \qquad . \quad (68)$$

Simple Ideal Low Pass Filter. It has already been shown that for the low pass filter

$$Z_1/2Z_2 = -\ \tfrac{1}{2}\omega^2 LC.$$

The limiting frequencies of the pass band from (67) are thus zero and

$$\omega_c = 2/\sqrt{(LC)} \qquad . \qquad . \qquad . \quad (69)$$

or

$$f_c = 1/\pi\sqrt{(LC)}.$$

This is called the *critical* or *cut-off* frequency.

Now by substitution,

$$-\ Z_1/4Z_2 = (\omega/\omega_c)^2.$$

The pass band characteristics from (66) are then

$$\left.\begin{aligned} \alpha &= 2\sin^{-1}(\omega/\omega_c) \\ \beta &= 0 \end{aligned}\right\} \qquad . \qquad . \quad (70)$$

From (68) the attenuating band gives

$$\left.\begin{aligned} \alpha &= \pi \\ \beta &= 2 \cosh^{-1} (\omega/\omega_c) \end{aligned}\right\} \qquad (71)$$

Equations (70) and (71) are plotted in Fig. 301.

It is interesting to note that the same results can be obtained from Campbell's loaded line formula, equation (65), Chapter XV, for if P_s is small $\cosh P_s \doteqdot 1$ and $\sinh P_s \doteqdot P_s$. Then

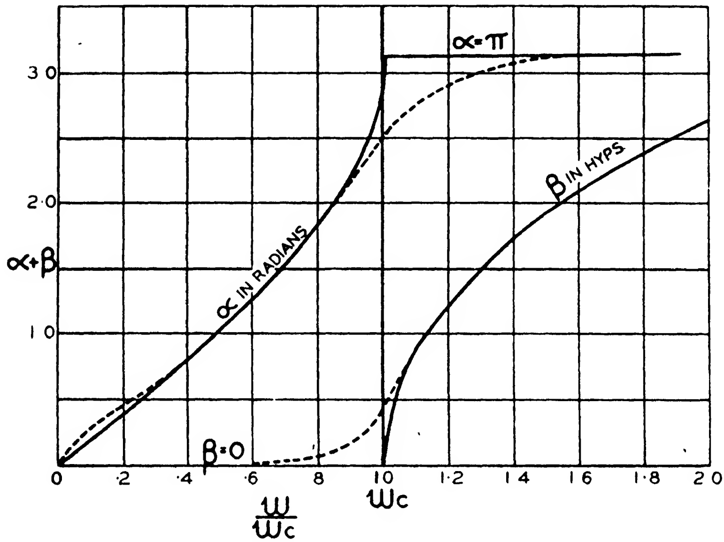


FIG. 301. TRANSMISSION CONSTANTS OF AN IDEAL LOW-PASS FILTER

$P_s/Z_0 = (G + j\omega C)s$ and since G is zero for an ideal circuit equation (65) becomes

$$\cosh P_s = (1 - \omega^2 LC_s)/2 = 1 + Z_1/2Z_2.$$

This proves the statement made when considering the loaded line that the cut-off frequency is the resonant frequency of a half-loading coil section; for this latter gives

$$\omega_c = 2/\sqrt{(LC_s)}$$

which is the same as (69) when it is noted that C_s corresponds to C in the case of the filter.

The characteristic impedance of a uniform line has been shown to be a relationship between series and shunt impedances.

In the case of recurrent networks such as filters, the same relation is termed the *image impedance* and can be defined as the impedance of a network when extended by similar networks indefinitely. It is also the impedance at the sending terminals of the network when it is terminated at the receiving terminals by an impedance equal to the geometric mean of the two sending end impedances, measured with the receiving end open-circuited and short-circuited respectively. The image impedance-frequency characteristic of a filter is important because the formulae given above apply only to a filter which is correctly terminated.

From the general equations the mid-series and mid-shunt image impedances the following can now be written

$$Z_{os} = \sqrt{\left\{\frac{L}{C}\left[1 - \left(\frac{\omega}{\omega_c}\right)^2\right]\right\}}$$

$$Z_{oD} = \sqrt{\frac{L/C}{1 - (\omega/\omega_c)^2}}$$

Putting $R_o = \sqrt{(L/C)}$ which is the impedance of the filter at zero frequency and termed the *nominal impedance*

$$\left.\begin{aligned} Z_{os} &= R_o\sqrt{[1 - (\omega/\omega_c)^2]} \\ Z_{oD} &= \frac{R_o}{\sqrt{(1 - (\omega/\omega_c)^2}} \end{aligned}\right\} \qquad . \qquad . \quad (72)$$

It is seen from (72) that the impedance is a pure resistance in the pass band and a pure reactance in the attenuating band, i.e. when ω/ω_c is greater than 1. For a mid-series section the reactance is positive and for a mid-shunt section the reactance is negative. Equations (72) are shown in Fig. 302.

Simple Ideal High Pass Filter. In this case

$$Z_1/2Z_2 = -8/\omega^2 LC.$$

From (67) the limiting frequencies of the pass band are ∞ and

$$\omega_c = 2/\sqrt{(LC)}.$$

The critical frequency of the low and high pass filters shown in Fig. 300 is thus identical, and whilst the former passes from zero to ω_c the latter passes from ω_c to infinity.

Putting $$-Z_1/4Z_2 = (\omega_c/\omega)^2.$$

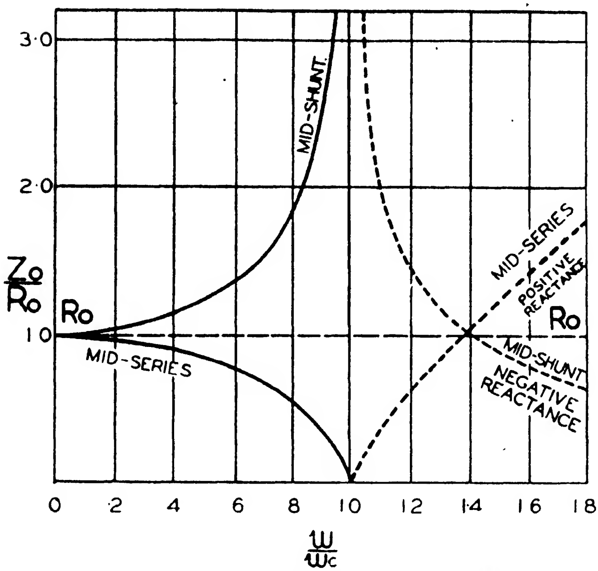


FIG. 302. IMAGE IMPEDANCES OF MID-SERIES AND MID-SHUNT IDEAL LOW-PASS FILTERS

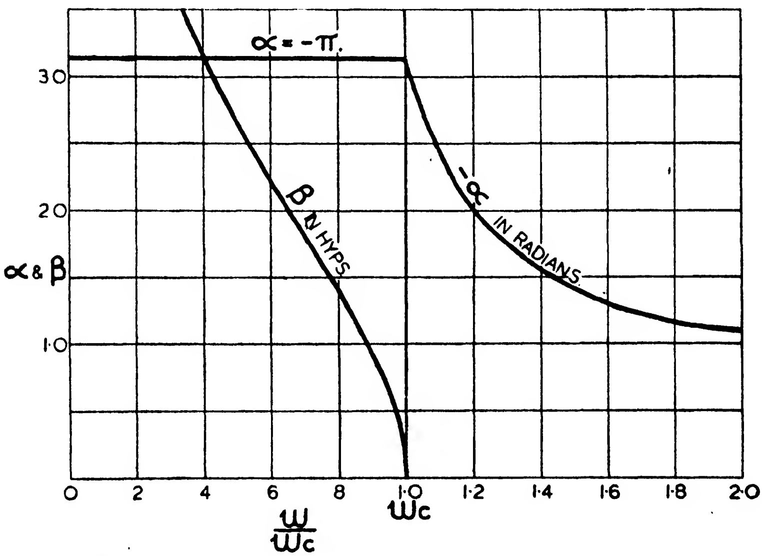


FIG. 303. TRANSMISSION CONSTANTS OF AN IDEAL HIGH-PASS FILTER

The pass band characteristics from (66) are

$$\left.\begin{aligned} \alpha &= 2 \sin^{-1} (\omega_c/\omega) \\ \beta &= 0 \end{aligned}\right\} \quad . \quad . \quad (73)$$

The attenuating band characteristics from (68) are

$$\left.\begin{aligned} \alpha &= -\pi \\ \beta &= 2 \cosh^{-1} (\omega_c/\omega) \end{aligned}\right\} \quad . \quad . \quad (74)$$

These equations are plotted in Fig. 303.

From the general equation the mid-series and mid-shunt image impedances are found to be

$$\left.\begin{aligned} Z_{os} &= R_o\sqrt{[1 - (\omega_c/\omega)^2]} \\ Z_{oD} &= \frac{R_o}{1 - (\omega_c/\omega)^2} \end{aligned}\right\} \quad . \quad . \quad (75)$$

These equations are plotted in Fig. 304.

Band Pass Filters. Here again the general formulae apply. A pass band will occur when $Z_1/4Z_2$ is between 0 and -1. In general there will be a number of pass bands depending upon the number of elements forming the series and shunt impedances.

Another way of forming band pass filters and one which is very frequently adopted, is to combine high and low pass filters. For example, a low pass filter with a cut-off frequency of 6 500 per sec. in series with a high pass filter with a cut-off frequency of 3 500 per sec. together form a band pass network with a pass band frequency of 3 500 to 6 500 per sec. (See Fig. 305.)

Mode of Operation of a Filter Circuit. The following considerations will help to make clear the mode of action of a filter circuit. In an ideal filter there is no resistance or leakance, no magnetic or dielectric hysteresis losses, and therefore the network cannot itself absorb any power. All power entering the network must be delivered up at the output terminals; there can be no attenuation of power. Above the cut-off frequency in the case of a low pass filter, and below the cut-off frequency in the case of a high pass filter, attenuation of current and voltage does take place, as has been shown, but the networks are completely reactive and there is no power entering

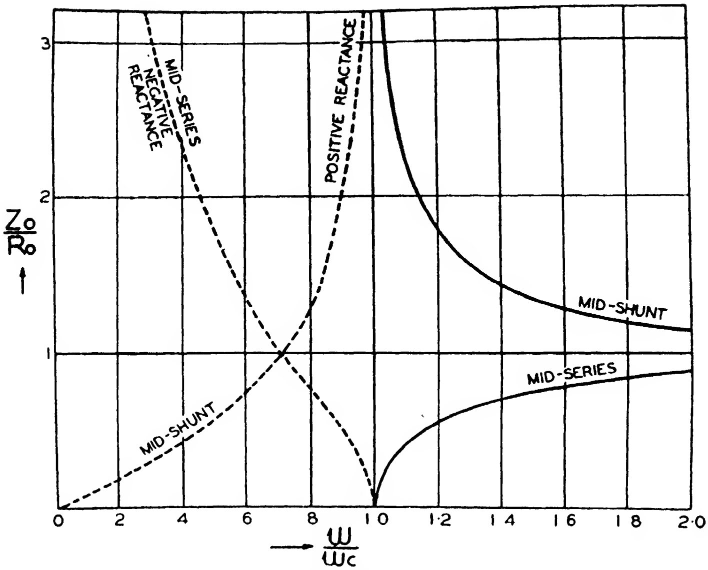
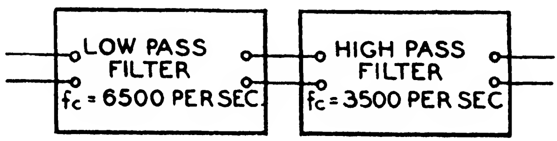


Fig. 304. Image Impedances of Mid-series and Mid-shunt Ideal High-pass Filter



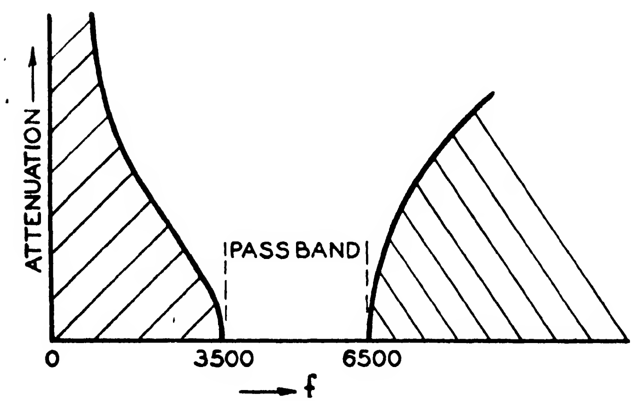


Fig. 305. Band-pass Filter Formed from High-pass and Low-pass Filters

the networks or at any point in them. Briefly, then, a filter discriminates against certain frequencies by becoming reactive.

Coil-loaded Lines as Low Pass Filters. It will be appreciated from the preceding sections that a coil-loaded line is in effect a series of simple low pass filters with the addition of considerable series resistance.

A comparison of curves *a*, *b* and *c*, Fig. 299, with the β curve in Fig. 301 shows the effect upon the attenuation of the series resistance, which, it must be remembered, is distributed uniformly with the capacitance.

The phase constant is also slightly modified as indicated by the dotted line in Fig. 301.

The filter theory also leads to the definition of the cut-off frequency as the frequency at which, neglecting losses, the attenuation ceases to be zero. (See British Engineering Standards Definition No. 9342.)

The coil-loaded line can also be considered as a series of mid-series or mid-shunt sections according as the line commences with a half-coil, or a half-section. The attenuation and phase constants are the same in either case, but the impedance-frequency characteristics will be similar to the mid-series and mid-shunt image impedance characteristics respectively, as shown in Fig. 302. The impedance-frequency curves of actual loaded lines show irregularities due to non-uniformity of the primary constants, variations in loading coil spacings and loading coil inductances, etc. Fig. 306 gives a typical measured impedance-frequency curve for a 40 lb. cable pair loaded with 120 mH. coils, with a half-section termination. It follows closely the characteristic curve of a mid-shunt filter, the chief difference being that it is not quite non-reactive. The angle is, however, less than 5° over the effective frequency range.

A study of filter theory is essential for a proper understanding of the action of a coil-loaded line, and in addition it helps to solve many problems connected with loaded lines which would be extremely complicated and difficult if tackled in a direct manner. An example has already been quoted—viz. Campbell's formula gives rigorously the attenuation of a loaded line—but simple low pass filter theory indicates the cut-off frequency in a simple manner. Using a resistanceless filter in this way to represent the line does not of course give correct results, but

the form of the attenuation or impedance curves, etc., is obtained. Two further examples will now be given, the effect of reflections on the terminal impedance of a coil-loaded line which is electrically short, and the effect of varying the length of cable between the sending end and the first loading coil.

Reflection Effects on Coil-loaded Lines. Coil-loaded lines are often comparatively short electrically, and therefore reflections from the distant end or from an impedance irregularity will have a serious effect on the sending end impedance. Reflection coefficients have been worked out in Chapter XIV, but the

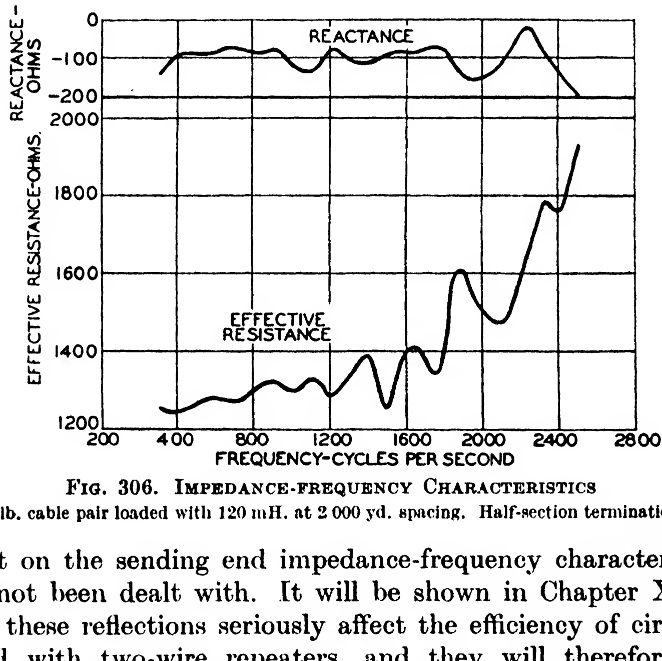


FIG. 306. IMPEDANCE-FREQUENCY CHARACTERISTICS
40 lb. cable pair loaded with 120 mH. at 2 000 yd. spacing. Half-section termination.

effect on the sending end impedance-frequency characteristic has not been dealt with. It will be shown in Chapter XVII that these reflections seriously affect the efficiency of circuits fitted with two-wire repeaters, and they will therefore be studied at this stage with the help of filter theory.

Consider first a simple ideal low pass filter terminated with a resistance R. The characteristic resistance of such a filter has been shown to be

$$Z_{OS} = R_o \sqrt{[1 - (\omega/\omega_c)^2]} \text{ mid-series type;}$$

$$Z_{OP} = R \frac{1}{\sqrt{[1 - (\omega/\omega_c)^2]}} \text{ mid-shunt type;}$$

where $R_o = \sqrt{(L/C)}$ and $\omega_c = 2/\sqrt{(LC)}$.

The sending end impedance from equation (18), Chapter XIV, is

$$Z_s = Z_o\left(\frac{R\cosh\theta + Z_o\sinh\theta}{Z_o\cosh\theta + R\sinh\theta}\right)$$

In the transmitting range $\theta = j\alpha$.

$$\therefore \quad Z_s = Z_o\left(\frac{R\cos\alpha + jZ_o\sin\alpha}{Z_o\cos\alpha + jR\sin\alpha}\right)^*$$

* *Note.* $\cosh j\alpha = \cos\alpha$.
$\sinh j\alpha = j\sin\alpha$.

By this equation the curve Z_s oscillates about the mean Z_o, and it is possible to sketch the curve by finding the maximum and minimum points.

When $\alpha = 0$, $180°$, $360°$, etc., $\sin\alpha = 0$ and $\cos\alpha = 1$ and $Z_s = Z_o\,(R/Z_o) = R$.

When $\alpha = 90°$, $270°$, etc., $\sin\alpha = 1$, $\cos\alpha = 0$ and $Z_s = Z_o^2/R$.

If R equals or nearly equals R_o the result is

$$\left.\begin{array}{ll} Z_s = R_o & \text{maximum points} \\ Z_s = R_o\,(1 - \omega^2/\omega_c^2) & \text{minimum points} \end{array}\right\} \text{mid-series type.}$$

and

$$\left.\begin{array}{ll} Z_s = \dfrac{R_o}{1 - \omega^2/\omega_c^2} & \text{maximum points} \\ Z_s = R_o & \text{minimum points} \end{array}\right\} \text{mid-shunt type.}$$

With a single section the total phase change from 0 to ω_c is 180°, and there is thus one oscillation in the Z_s curve. With a filter of n sections the total phase change will be n times 180°, and there will be n oscillations in the Z_s curve. Fig. 307 shows a Z_s curve for a four-section mid-series filter.

Effect of End Section on Terminal Impedance. It has been stated that half-section or half-coil terminations are used where possible on loaded lines, the former being the more usual. For geographical reasons, however, the first and last coils cannot always be placed to give exactly half a section, and when this is the case the terminal impedance is affected.

Consider a coil-loaded line for which the first section is l miles longer than a half-section. (See Fig. 308.) Let the first

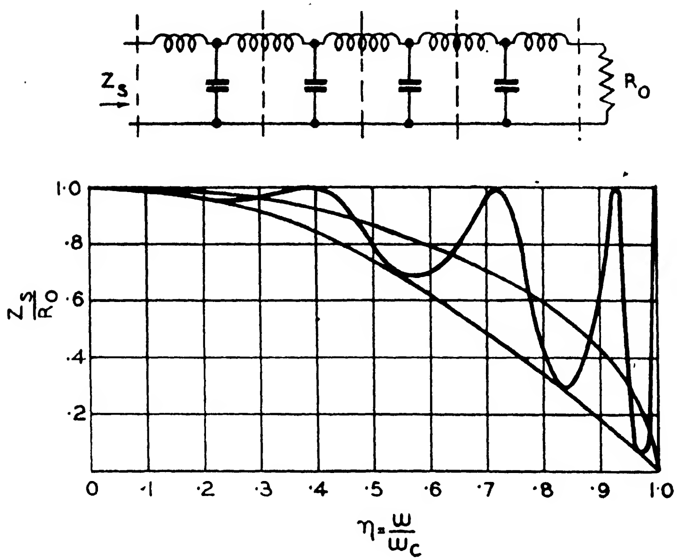


FIG. 307. TERMINAL IMPEDANCE OF A FOUR-SECTION MID-SERIES FILTER

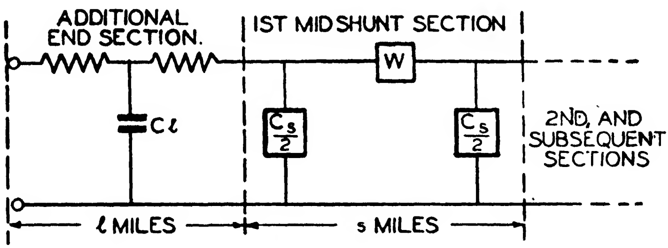


FIG. 308. LINE TERMINATED WITH ADDITIONAL END-SECTION

section be expressed as a fraction x of the normal spacing distance s miles, then

$$l = s\,(x - \tfrac{1}{2}) \text{ and } x = (l + \tfrac{1}{2}s)/s.$$

The mid-shunt impedance of the loaded cable regarded as a resistanceless filter is

$$Z_{on} = R_o \frac{1}{\sqrt{\left[1 - \left(\dfrac{\omega}{\omega_c}\right)^2\right]}}$$

where $$R_o = \sqrt{(L/C_s)},\ \omega_c = 2/\sqrt{(LC_s)}.$$

The constants of the unloaded cable are

$$Z_o \doteqdot \sqrt{(R/j\omega C)},\ P \doteqdot \sqrt{(Rj\omega C)}.$$

The terminal impedance Z_s is given by equation (18), Chapter XIV,

$$Z_s = Z_o\left(\frac{Z_{oD}\cosh Pl + Z_o \sinh Pl}{Z_o \cosh Pl + Z_{oD}\sinh Pl}\right)$$

Since l is short electrically, $\cosh Pl \doteqdot 1$, $\sinh Pl \doteqdot Pl$.

$$Z_s \doteqdot Z_o\left(\frac{Z_{oD} + Z_o Pl}{Z_o + Z_{oD}Pl}\right)$$

$$\doteqdot \frac{Z_{oD} + Z_o Pl}{1 + Z_{oD}Pl/Z_o}$$

By putting values into this equation it will be found that $Z_o Pl$ is very small compared with Z_{oD}. Also $Pl/Z_o \doteqdot j\omega CL$.

$$\therefore\quad Z_s \doteqdot \frac{Z_{oD}}{1 + j\dfrac{\omega CLR_o}{\sqrt{[1-(\omega/\omega_c)^2]}}}$$

By substituting

$$Z_s \doteqdot \frac{R_o\dfrac{1}{\sqrt{[1-\omega^2/\omega_c^2]}}}{1 + j(x-\tfrac{1}{2})\left[\dfrac{2(\omega/\omega_c)}{\sqrt{(1-\omega^2/\omega_c^2)}}\right]}$$

From this resistance and reactance components of Z_s are found to be

$$\left.\begin{aligned} R &\doteqdot \frac{R_o\sqrt{[1-\omega^2/\omega_c^2]}}{1 + 4x(\omega^2/\omega_c^2)(x-1)} \\ X &\doteqdot \frac{R_o(\omega/\omega_c)(1-2x)}{1 + 4x(\omega^2/\omega_c^2)(x-1)} \end{aligned}\right\} . \qquad (76)$$

The resistance and reactance frequency curves from equation (76) are plotted in Fig. 309 and for different values of x.

Attenuation Equalizer Networks. The attenuation distortion which occurs with unloaded or lightly loaded lines has a serious effect upon the transmission efficiency of long circuits (long electrically). There are two methods by which this distortion can be readily reduced, viz.—

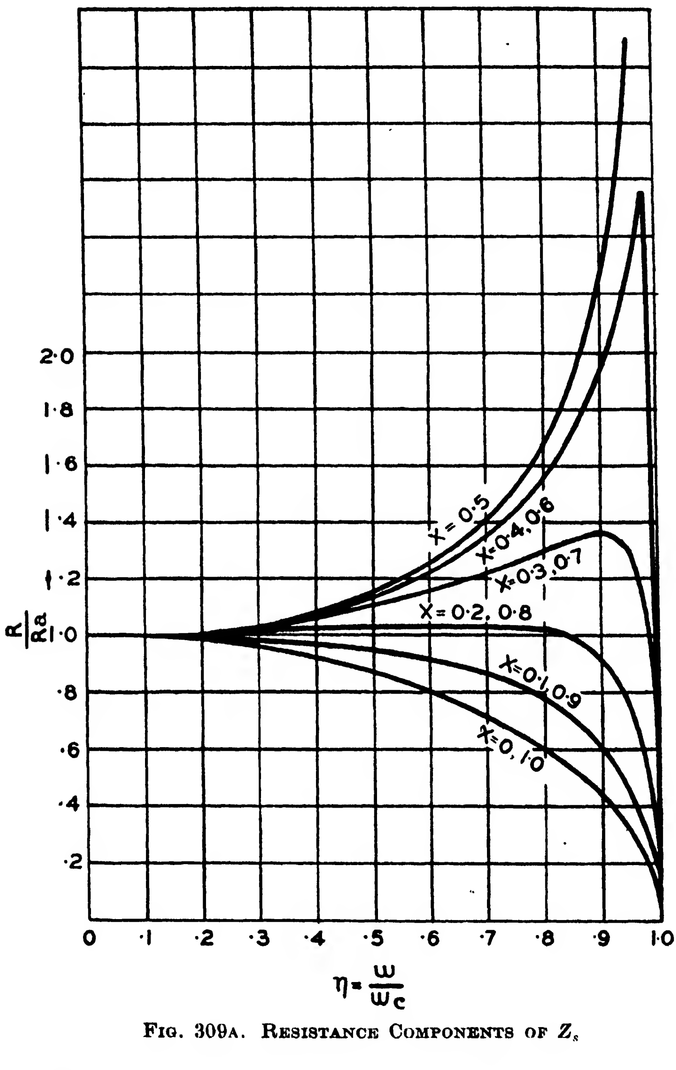
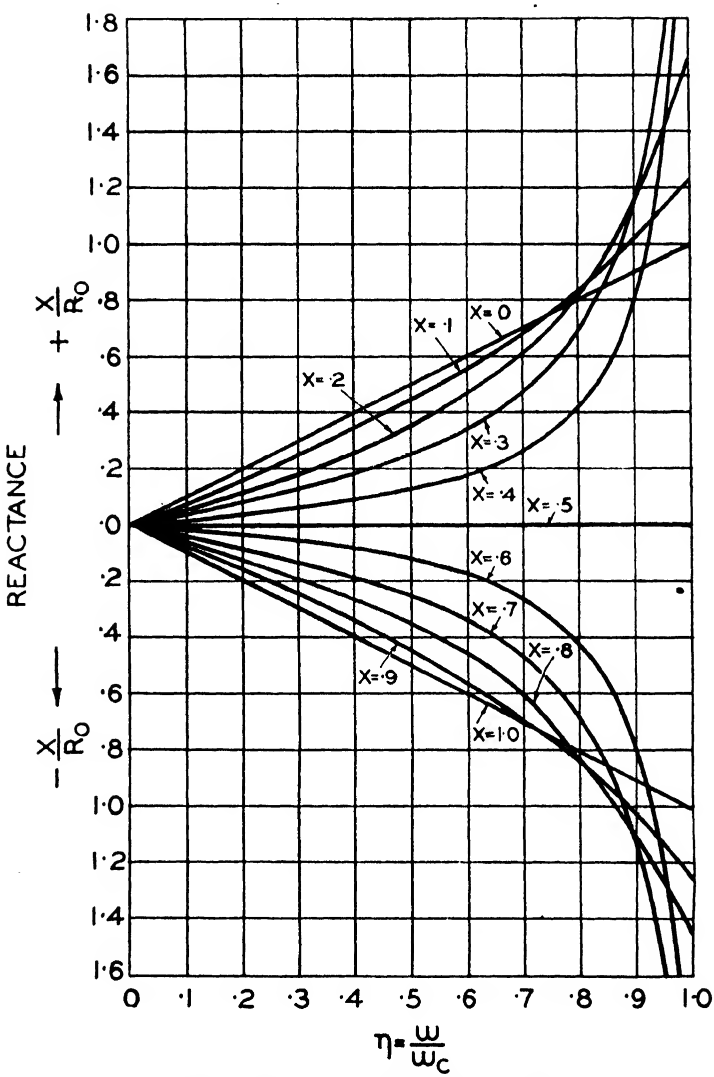


FIG. 309A. RESISTANCE COMPONENTS OF Z_s

(*a*) When a circuit includes valve amplifiers, to arrange that the amplifiers give increased amplification at certain frequencies to compensate for increased attenuation on the line.

(*b*) To insert a network between the line and the valve amplifiers having an attenuation frequency characteristic which is the inverse of the line characteristic, so that the sum



309B. REACTANCE COMPONENTS OF Z_s

attenuation of line plus network is sensibly a constant over the effective frequency range.

The first method, details of which are given in Chapter XVII, is used mainly on circuits in coil-loaded cables to compensate for increased attenuation towards the cut-off frequency, and

so gives a somewhat wider effective frequency band than would otherwise be obtained. The second method is employed mainly on unloaded and lightly loaded conductors to compensate over a wide frequency range for a rising attenuation-frequency characteristic. An equalizing network is inserted between the line and the input side of an amplifier having an impedance which is a plain resistance, usually 600 or 1 000 ohms. It is convenient to employ therefore what is known as a *constant resistance* network, of the same value as the amplifier, for by

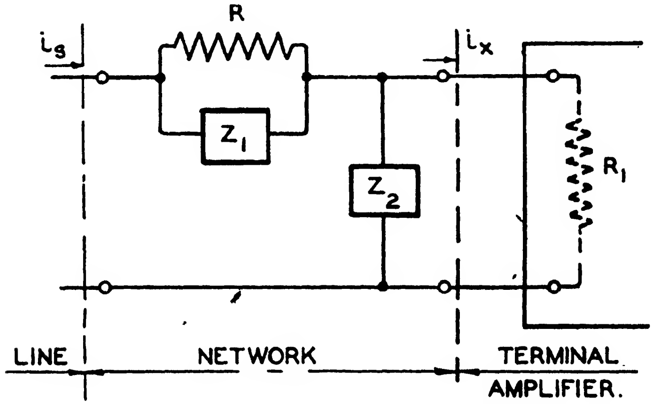


FIG. 310. CONSTANT RESISTANCE EQUALIZER

so doing any reflection effects which take place between the line and the amplifier remain unaltered by the insertion of such a network. The insertion loss is then simply the attenuation of the network.

The theory of the simplest form of constant resistance network is as follows. Taking an 'L' network as shown in Fig. 310, the series element consists of a resistance equal to the terminal resistance R in parallel with a reactive network Z_1. The shunt element consists of a reactive network Z_2 having the inverse characteristic of Z_1 such that

$$Z_1 Z_2 = R^2 \quad . \quad . \quad . \quad . \quad (a)$$

The impedance presented to the line is obviously

$$Z_s = \frac{RZ_1}{R + Z_1} + \frac{RZ_2}{R + Z_2}$$

Substituting for Z_2 from (a)

$$Z_s = \frac{R\,(R + Z_1)}{R + Z_1} = R \text{ a constant.}$$

Thus proving that the terminal impedance is unaffected by the insertion of the network. Terminal reflections therefore remain unchanged.

If $\theta = \beta + j\alpha$ is the propagation length of the network,

$$v_s/v_x = i_s/i_x = \varepsilon^\theta$$
$$= (Z_2 + R)/Z_2 = 1 + R/Z_2.$$

Substituting from (a)

$$\varepsilon^\theta = 1 + Z_1/R.$$

If $Z_1 = R_1 + jX_1$,

$$\varepsilon^\theta = (1 + R_1/R) + j\,(X_1/R).$$

The modulus of this equation gives the voltage ratio v_r

$$v_r = \varepsilon^\beta = \sqrt{[(1 + R_1/R)^2 + (X_1/R)^2]} \quad . \quad (77)$$

The phase change through the network is of course

$$\varepsilon^{j\alpha} = \tan^{-1}[X/(R + R_1)] \text{ radians.}$$

For a given terminal resistance R therefore the attenuation is controlled entirely by the value of Z_1. The required loss with zero reactance, $X_1 = 0$ enables R_1 to be found; then

$$\left.\begin{aligned} \varepsilon^\beta &= 1 + R_1/R \\ \text{or} \quad R_1 &= (\varepsilon^\beta - 1)R \end{aligned}\right\} \quad . \quad . \quad . \quad (78)$$

The required loss-frequency characteristic is thus obtained by suitably designing Z_1. The actual design is often a matter of some difficulty and involving much trial and error method and requiring some experience.

When Z_1 has been fixed it remains only to find the inverse network Z_2 from equation (a).

$$Z_2 = R^2/Z_1.$$

Consider two pairs of inverse impedances for which

$$\text{(i)} \quad Z_1 Z_2 = R^2$$
$$\text{(ii)} \quad z_1 z_2 = R^2$$

Put Z_1 and z_1 in series, and Z_2 and z_2 in parallel: then the combined impedances are also inverse networks for

$$(Z_1 + z_1)\left(\frac{Z_2 z_2}{Z_2 + z_2}\right) = \frac{Z_1 Z_2 z_2 + z_1 z_2 Z_2}{Z_2 + z_2}$$
$$= R\,\frac{z_2 + Z_2}{Z_2 + z_2} = R$$

Therefore the rule is that if one network Z_1 is composed of elements in series, then the inverse network Z_2, given by $Z_1Z_2 = R^2$, is composed of elements in parallel and vice versa. Further, the individual elements of one network must each

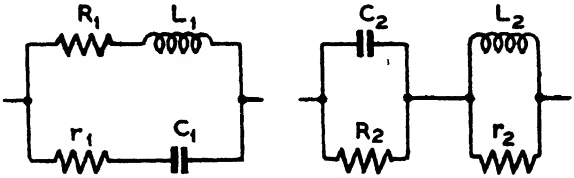


FIG. 311. INVERSE NETWORK

be the inverse of the corresponding elements of the other impedance and related thus—

$$\left.\begin{array}{ll} \text{If} & Z_1 = z_{11} + z_{12} + z_{13} \ldots \\ \text{then} & \dfrac{1}{Z_2} = \dfrac{1}{z_{21}} + \dfrac{1}{z_{22}} + \dfrac{1}{z_{23}} \\ \text{where} & Z_1Z_2 = z_{11}z_{21} = z_{12}z_{22} = z_{13}z_{23} = R^2 \end{array}\right\} \quad (79)$$

Considering the elements themselves, the inverse of an element which is a pure inductance is a pure capacitance and vice versa, for

$$j\omega L \, . \, 1/j\omega C = L/C = R.$$

Then resistances, capacitances and inductances in Z_1 become resistances, inductances and capacitances respectively in Z_2 such that

$$R_1/R_2 = C_1/L_2 = L_1/C_2 = R^2 \quad . \quad . \quad (80)$$

Fig. 311 shows two typical inverse networks.

Transmission Time and Phase Distortion on Coil-loaded Lines. The velocity of propagation of continuous single frequencies is $S = \omega/\alpha$ (equation (20), Chapter XIV).

For coil-loaded lines therefore from (70)

$$S = \frac{\omega_s}{2 \sin^{-1} (\omega/\omega_c)} \quad . \quad . \quad . \quad . \quad (81)$$

where S is the spacing of the coils.

For frequencies remote from the cut-off, where α is proportional to frequency, $S = 1/\sqrt{(LC)}$. This is the velocity on the

equivalent smooth line, L and C being values per mile. The transmission time per mile is then $t = \sqrt{(LC)}$. When the phase constant α is not proportional to frequency, differences

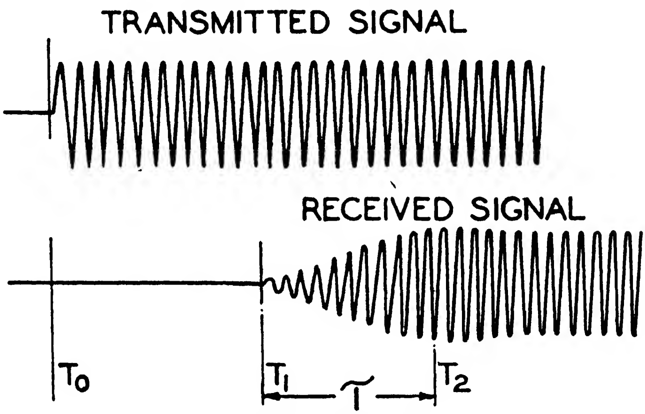


FIG. 312. TIME OF TRANSMISSION OF A SIGNAL

will occur in the transmission times of various frequencies and phase distortion is said to exist.

Now speech waves consist of a mixture of many frequencies, but the actual phase relationship of the frequencies is not important. In telephone transmission, therefore, interest is confined to the group velocity of the frequencies, i.e. the velocity of the envelope. It can be shown that a measure of the group velocity is given by $1/da/d\omega$ and the transmission time of the circuit by

$$T = da/d\omega \quad . \quad . \quad . \quad . \quad (82)$$

where $a = \alpha \times$ the attenuation length of the line.

A signal applied at a time T_0 at one end of a transmission system first makes its appearance at the other end at a time T_1, the minimum value of $da/d\omega$ in the transmission band. The steady state value of the received signal is attained after a time T_2, the value of $da/d\omega$ at the signal frequency. Fig. 312 illustrates this transient effect. The reason for this is that when the signal is first started, frequencies covering the whole frequency spectrum are transmitted. That these frequencies are produced will be evident by regarding the signal frequency as being modulated by a d.c. signal; and a d.c. signal, as is well

known, can be regarded as a signal comprising all the odd harmonics from zero to infinity. The building up period from T_1 to T_2 is known as the *transitory* period.

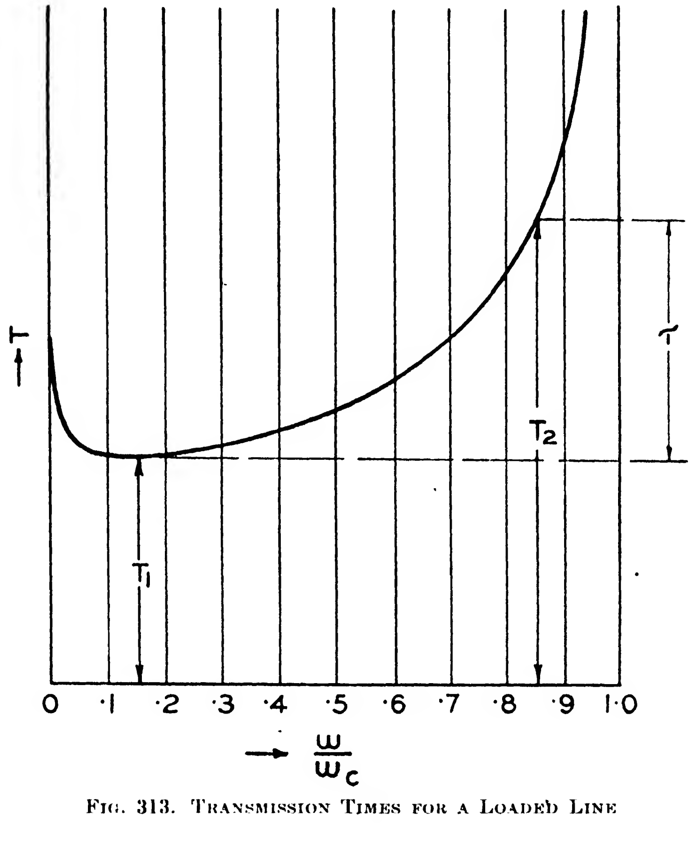


FIG. 313. TRANSMISSION TIMES FOR A LOADED LINE

Since $\alpha l = a = 2l \sin^{-1} (\omega/\omega_c)$;

$$\left.\begin{aligned} T &= \frac{da}{d\omega} = \frac{2l}{S\omega_c} \cdot \frac{1}{\sqrt{(1 - \omega^2/\omega_c^2)}} \\ \text{and} \quad T_1 &= 2l/S\omega_c \\ \therefore \quad \mathrm{T} &= \frac{T_1}{\sqrt{[1 - (\omega/\omega_c)^2]}} \end{aligned}\right\} \quad (83$$

Fig. 313 shows T plotted against ω for a typical loaded line.

From equation (83) the transitory period is

$$\tau = T_2 - T_1 = T_1\left[\frac{1}{\sqrt{(1-\omega^2/\omega_c^2)}} - 1\right] \quad . \quad (84)$$

For frequencies remote from the cut-off the binomial approximation gives

$$\tau \doteqdot l\omega^2/S\omega_c^3 \quad . \quad . \quad . \quad . \quad (85)$$

On very long lines with heavy loading, phase distortion and the resulting transient effects may cause loss of intelligibility,

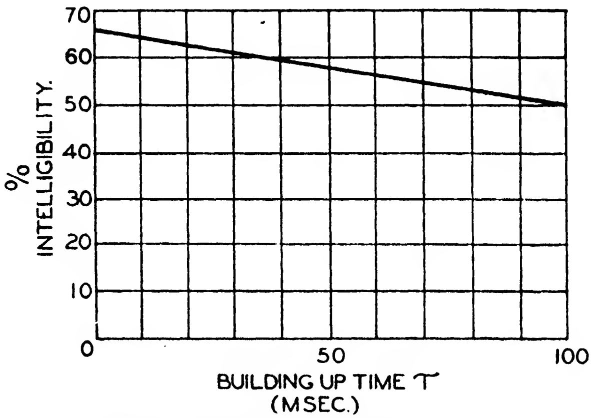


Fig. 314. Effect of Transitory Period on Intelligibility

particularly as it will mainly affect the consonants. The observed effect is a peculiar whistling sound accompanying the transmitted speech. The effect upon syllabic articulation is shown in Fig. 314. It has been agreed by the C.C.I.F. that the maximum transmission time for a complete Continental communication should not exceed 250 msec., and that the transitory period for the highest frequency effectively transmitted should not exceed 30 msec.

The table on page 411 shows the lengths of various types of loaded line which would give 250 msec. transmission time and 30 msec. transitory period at 2 600 per sec. frequency.

It will be seen that on long lines with heavy or medium heavy loading, phase distortion may become serious. Phase correcting networks can be inserted to equalize the transmission time, in the same way as attenuation equalizer networks. For music or facsimile transmissions, which are more

TABLE 6

Loading (mH. at 2 000 yd.)	Length of Line (in miles) giving	
	250 msec. delay	30 msec. transitory period
176	2 500	154
120	3 050	680
88	3 570	1 360
44	5 000	4 770
22	7 150	12 000

sensitive to phase distortion, high velocity of propagation is essential. For music it is desirable that the transitory period should be less than 5 msec.

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CHAPTER XVII

VALVES AND REPEATERS

Necessity for Repeaters. It has been stated in Chapter XV that satisfactory telephonic communication cannot be carried on if the attenuation between the telephones greatly exceeds 30 db. In practice, considerable losses are introduced by exchange switching equipment: the losses are caused principally by condensers in series with the line and by relays and impedance coils bridged across the line. In addition, large losses must be allowed for in the connections between the telephones and the exchanges to which they are connected. As shown in Chapter XX, this loss is due partly to the attenuation of the local telephone line and, in the case of the central battery instrument, partly to the reduced efficiency of the transmitter with the reduced transmitter current due to the ohmic resistance of the line. This latter may be very considerable, and at least 10 db. must be allowed for it.

The maximum permissible loss which may be introduced by the lines in a complete telephone connection is thus limited to something of the order of 15 db. With unloaded cable only very limited distances can be covered within this maximum loss; by heavy loading this distance can be increased roughly four times, and by the use of heavy aerial conductors fairly long distances can be covered, but ultimately, however, some amplifying device to compensate for line attenuation becomes essential.

Amplifiers, or *repeaters* as they are called, enable telephonic communications to be made over long distances which would otherwise be impossible, and in addition, enable firstly long aerial lines to be dispensed with, and secondly the weight of cable conductors to be reduced. Circuit design becomes therefore a question of economics, the weight of cable conductor, the loading, and the spacing of the amplifiers being chosen to give the most economical circuit. Both initial and maintenance costs must of course be considered. In the case of the aerial line, however, one of the principal considerations is its liability

to faults or complete breakdown under adverse weather conditions.

The first amplifiers were relay devices employing a telephone receiver coupled directly to a transmitter button; current for the transmitter being supplied from a local battery. Quite good results were obtained, but the introduction of the thermionic valve provided an amplifying device without any moving parts and requiring no mechanical adjustments, which immediately superseded relay devices before they were perfected.

The thermionic valve is now so well known that no general description of its mode of operation is necessary, and its electrical characteristics can be given at once.

The Diode Valve. When the cathode of such a valve is heated directly or indirectly electrons are emitted at a rate dependent upon the temperature and upon the chemical composition of the cathode. The electrons are negative charges repelling one another, and the cathode is left with a positive charge. The cathode is in a vacuum, and the electrons which have been given off constitute a *spacecharge* which ultimately reaches a limiting value when as many electrons are forced back to the cathode per second as leave it per second. When an anode with a positive potential is introduced, electrons are drawn off and more leave the cathode to take their place. If the potential of the anode is increased more electrons are drawn off; the maximum occurring when all electrons leaving the cathode reach the anode, none returning to the cathode. This stream of electrons to the anode constitutes an anode current ($6 \cdot 3 \times 10^{18}$ electrons per sec. = 1 ampere). If the anode potential were reversed the space charge would be assisted instead of opposed and the return of electrons to the cathode would be assisted, and so no anode current would flow. The two-electrode valve is thus a rectifying device.

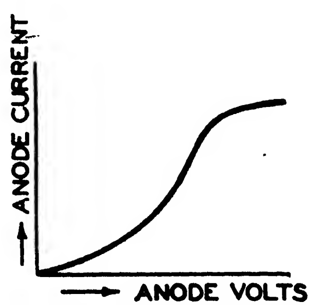


FIG. 315. CHARACTERISTICS OF A DIODE VALVE

Diode Rectification. A valve with two electrodes, anode and cathode, is termed a *diode* valve. Fig. 315 shows the characteristics of a diode:

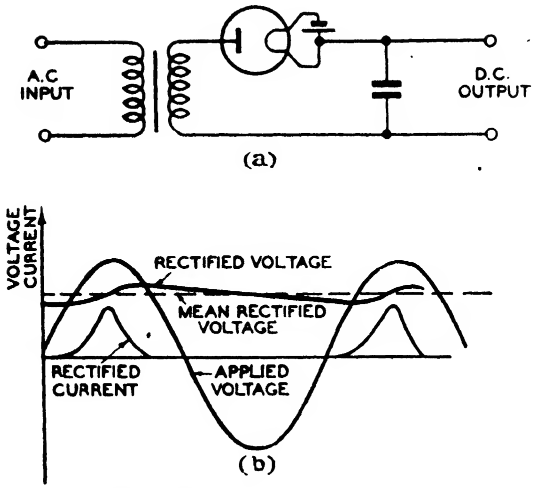


FIG. 316. HALF-WAVE RECTIFIER CIRCUIT

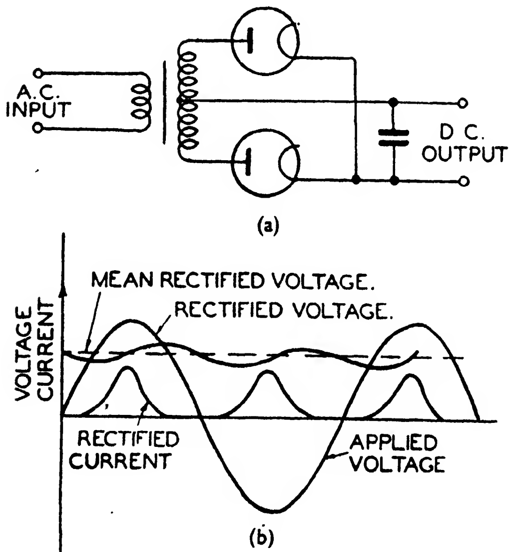


FIG. 317. FULL-WAVE RECTIFIER CIRCUIT

anode current is plotted against anode volts for a particular cathode temperature. A rectifying circuit can be arranged as shown at (*a*), Fig. 316. Current flows in the output circuit during the positive half-cycle only, and the circuit is therefore called a *half-wave* rectifier.

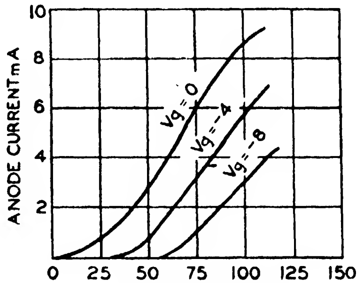


Fig. 318
Anode Characteristics

A condenser is usually fitted, as shown, to smooth the rectifier output by absorbing power during the positive half-cycle and discharging it during the negative half-cycle. Fig. 316 (*b*) shows graphs of the applied voltage and the rectified current and voltage (not to the same scales).

By using two diode valves as shown in Fig. 317 (*a*) both negative and positive half-cycles can be utilized and such a circuit is termed a full-wave rectifier. Current and voltage curves for this circuit are shown in Fig. 317 (*b*).

The Triode Valve. The third electrode termed the grid is in

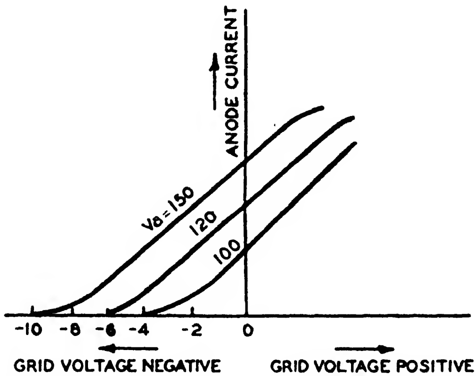


Fig. 319. Mutual Characteristics of a Triode

the form of a wire spiral between the cathode and the anode and it exercises a controlling influence according to its potential upon the flow of electrons from cathode to anode. The anode current-anode volts characteristics as shown in Fig. 318 are then modified according to the grid potential. Fig. 319 shows typical characteristics with grid voltages between 0 and $-$ 8.

As valves are usually worked with a fixed anode voltage useful curves are obtained by plotting anode current against grid voltage. These curves are termed the mutual characteristics.

It will be seen from Fig. 319 that a small change of grid potential will produce as large a change of anode current as would cause quite a large change of anode potential. Hence the amplifying properties of the triode valve.

The relation between the change of anode voltage required to produce a given small change of anode current to the change of grid voltage required to produce the same change of current is termed the *amplification factor of the valve.* The anode voltage

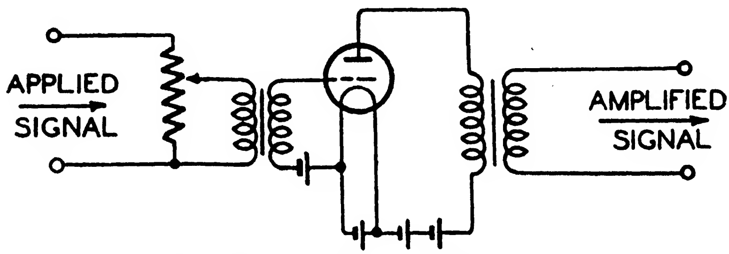


FIG. 320. TRIODE AMPLIFYING CIRCUIT

is required to be constant whilst determining the change of anode current.

The Triode Valve as an Amplifier. An amplifying circuit can be arranged as shown in Fig. 320.

In order to avoid non-linear distortion, i.e., the distortion produced when current is not directly proportional to applied voltage, the following conditions must be observed.

(i) The valve must operate on the straight portion of the mutual characteristic.

(ii) The voltage variations produced in the anode circuit must be limited to the straight portion of the anode characteristic. With zero signal voltage therefore the valve must be operating at the mid-point of this straight portion of the curve.

(iii) The grid must be given a negative bias so that the maximum positive signal to be applied will not give it a positive potential. If the grid were to become positive it would collect electrons as the anode does and a grid current would flow. This would result in distortion due to damping of the input circuit.

The static characteristics will now be dealt with, i.e. the characteristics of the valve itself. The anode current is given by the empirical formula

$$I_a = a\,(V_a + \mu V_g + c)^n \quad . \quad . \quad . \quad (86)$$

where a, c, and n are constants. For the straight portion of the characteristic $n = 1$ and

$$I_a = a\,(V_a + \mu V_g + c) \quad . \quad . \quad . \quad (86a)$$

Only changes of current and voltage are of importance, so that

$$\delta I_a = a\delta V_a + a\mu\delta V_g \quad . \quad . \quad . \quad (87)$$

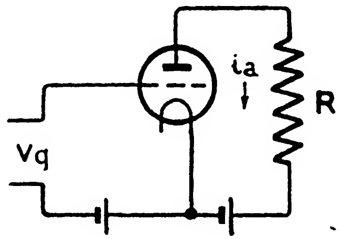


FIG. 321. BASIC AMPLIFIER CIRCUIT

For simplicity write i_a, v_a, and v_g for δI_a, δV_a, and δV_g respectively; then

$$i_a = av_a + a\mu v_g \quad . \quad . \quad . \quad (87a)$$

Differentiating with respect to v_a

$$di_a/dv_a = a.$$

This is a constant and is obviously a conductance. Its reciprocal is termed the *internal resistance* R_a.

$$dv_a/di_a = i/a = R_a \quad . \quad . \quad . \quad (88)$$

Differentiating (87a) with respect to v_g;

$$di_a/dvg = \mu a = \mu/R_a = g \quad . \quad . \quad (89)$$

This again is a constant termed the *mutual conductance* g. It is usual to express it in milliamperes per volt.

Multiplying (88) and (89),

$$dv_a/dv_g = \mu \quad . \quad . \quad . \quad . \quad (90)$$

This is the amplification factor already referred to.

Consider the valve with its associated circuit, Fig. 321,

again to obtain the dynamic characteristics of the amplifier. Writing equation (87*a*) in the following form

$$i_a = (1/R_a)\,(v_a + \mu v_g) \quad . \quad . \quad . \quad (91)$$

the signal voltage applied is v_g and as the anode voltage increases the anode potential falls due to the voltage drop in the load resistance R. Therefore $v_a = -\,Ri_a$.

Substituting in (91),

$$i_a = (1/R_a)\,(-\,Ri_a + \mu v_g).$$

The amplified signal is the voltage across R which is

$$Ri_a = \mu v_g R/(R + R_a)$$

$$= \frac{\mu v_g}{1 + R_a/R} \quad . \quad . \quad . \quad . \quad (92)$$

The true amplification i.e. the ratio of amplified to applied signal, is then

$$\mu_a = \frac{\mu}{1 + R_a/R} \quad . \quad . \quad . \quad (93)$$

The power output is

$$W = Ri_a^2 = \mu^2 v_g^2 R/(R + R_a)^2 \quad . \quad . \quad (94)$$

This is obviously a maximum when $R = R_a$, i.e. when the load impedance equals the internal impedance of the valve. Therefore

$$W_{max} = v_g^2\mu^2/4R^2 \quad . \quad . \quad . \quad (95)$$

It will be seen from equation (93) that when the amplifier is designed to give maximum power output with a given signal voltage, the amplification is half the amplification factor of value. This is not, however, the condition for maximum undistorted output of the amplifier, for which the load impedance R should be approximately twice the internal impedance of the valve R_a.

The working characteristics of an amplifier and the undistorted output which can be obtained can be conveniently shown by what is known as a *load line* drawn across the anode characteristics as shown in Fig. 322.

As already shown for the circuit in Fig. 321,

$$R = -\,v_a/i_a = \cot\theta$$

and thus the external load R is represented by the line AB on

the anode characteristic. The point A is fixed by the potential of the anode battery, the point B by the current which would produce a voltage drop in R equal to the potential of the

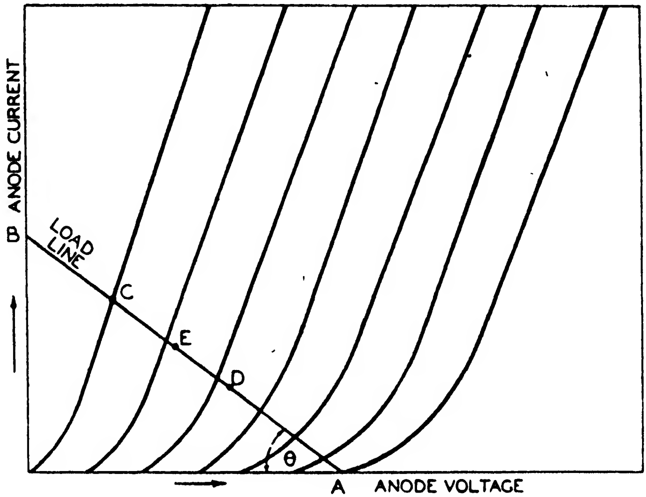


FIG. 322. LOAD LINE DIAGRAM

battery. The working point of the valve is therefore somewhere on the line AB according to the grid potential. The working limits must be first the zero grid voltage line point C, and second the point where the load line is cut by a curving characteristic point D. With no signal the valve should be working at point E midway between C and D; this is the required grid priming voltage.

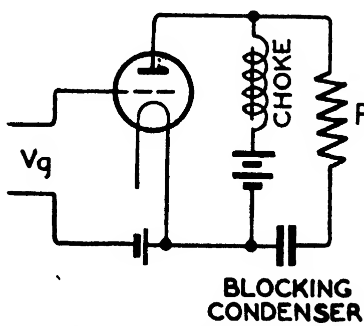


FIG. 323. CHOKE COUPLED AMPLIFIER

When the circuit is arranged as shown in Fig. 323 with the anode battery connected via a choke circuit instead of via the load impedance, the position of the load line is altered as shown in Fig. 324. If the load impedance remains the same, the load line has the same slope as the original line AB in Fig. 322, but as there is practically no d.c. voltage drop in the anode feed

the working point E is shifted to the voltage A, and a new load line $A'B'$ is obtained. When the load impedance is reactive

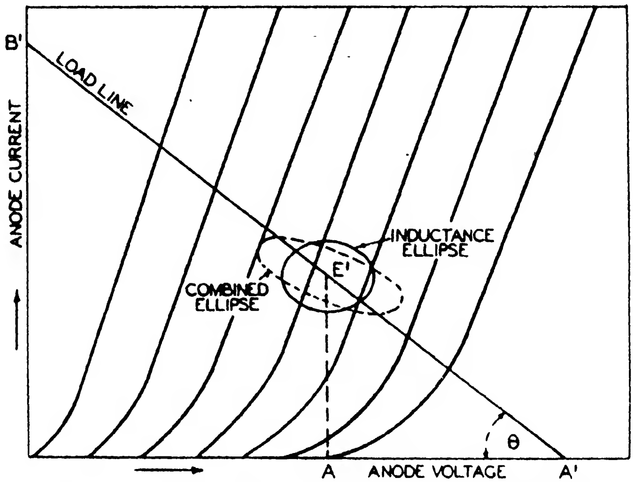


FIG. 324. LOAD LINE FOR CHOKE-COUPLED AMPLIFIER

it can be shown that the load line becomes an ellipse as indicated by the dotted line on Fig. 324.

Measurement of the Static Characteristics of a Triode. Fig. 325

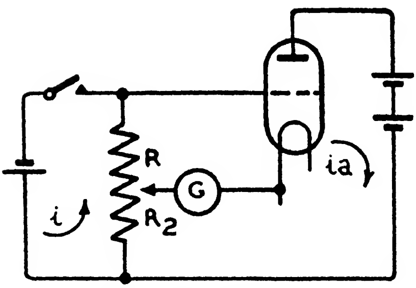


FIG. 325. MEASUREMENT OF μ

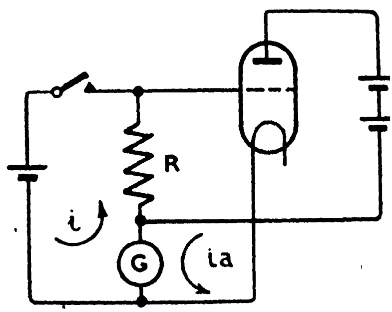


FIG. 326. MEASUREMENT OF R_a

shows a circuit by which the amplification factor μ of a valve can be measured directly.

The potentiometer is adjusted so that no change in the anode current is indicated by the galvanometer when the key is depressed. The depression of the key decreases the potential of the grid by iR_1 volts. This would cause a decrease of anode

current were it not compensated by an increase of anode potential iR_2 volts. Then

$$iR_1 = v_g$$

$$iR_2 = v_a$$

and

$$v_a/v_g = \mu = R_2/R_1 \quad . \quad . \quad . \quad (96)$$

Fig. 326 shows a circuit by which the internal impedance of a valve can be found directly.

The value of R is adjusted so that no change of deflection is indicated by the galvanometer when the key is depressed. Then the local current i equals the change of anode current and

$$iR = v_g$$

$$i = i_a$$

$$\therefore \frac{v_g}{i_a} = \frac{iR}{i} = R \quad . \quad . \quad . \quad . \quad (97)$$

This is termed the *mutual impedance*, R_m

Multiplying (96) and (97)

$$(v_a/v_g) \cdot (v_g/i_a) = v_a/i_a,$$

or

$$\mu R_m = R_a.$$

In practice the circuits shown in Figs. 325 and 326 can be modified so that the tests can be carried out with alternating current.

Repeaters. Telephone circuits must be capable of transmitting speech in both directions. From this requirement arise many of the difficulties encountered in introducing amplifiers into telephone lines. A simple valve amplifier such as that shown in Fig. 320 is essentially a one-way circuit, and to cater for both directions of transmission a special circuit, or *two-wire repeater*, as it is termed, is necessary. Alternatively, two separate lines equipped with unidirectional amplifiers can be used for the two directions of transmission, constituting a four-wire circuit.

Single Valve Two-wire Repeater. The simplest valve amplifier which will give two-way transmission is shown in Fig. 327. The principle is due to Edison.

The operation of this circuit is as follows.

Suppose speech currents arrive from the west line, then a

voltage is produced across the points X and Y—that is, across the grid circuit potentiometer G—this voltage is amplified and induced back into the line via the transformer, which is termed a *hybrid coil.* This coil has equal numbers of turns in the east

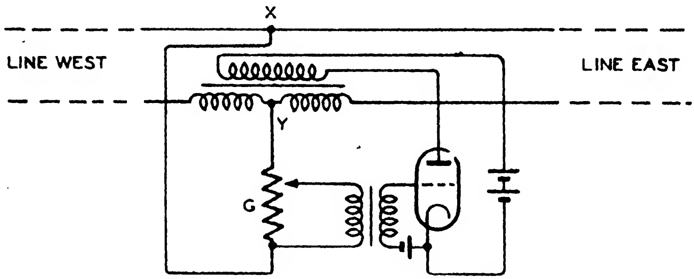


FIG. 327. SINGLE-VALVE TWO-WAY REPEATER

and west line windings, and thus if the lines have the same impedance no voltage will be produced across X and Y by the amplified signal. That this is so can be seen by drawing the

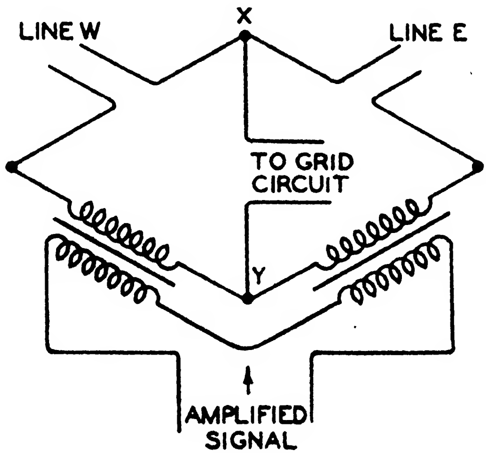


FIG. 328. HYBRID COIL BRIDGE CIRCUIT

circuit in the form of a Wheatstone bridge as shown in Fig. 328. The amplified signal induces equal e.m.f.'s in the two arms of the bridge, and if the bridge is balanced by the two lines no current will flow in the grid circuit. If the line impedances are not equal, an e.m.f. will be produced across G, which if it

exceeds the original received signal voltage across G will cause the amplifier to generate oscillations or 'sing' as it is termed. For satisfactory transmission of speech the circuit must be perfectly stable, i.e. have no tendency to oscillate, and therefore the amount by which a circuit can be improved by inserting this type of two-wire repeater depends upon the degree of impedance balance between the two lines. It will be seen that this bridge circuit enables a two-wire circuit to be transformed into a four-wire circuit. In this case, referring to Fig. 328, the east line is replaced by an artificial line or balancing network having the same impedance, so far as possible, as the west line.

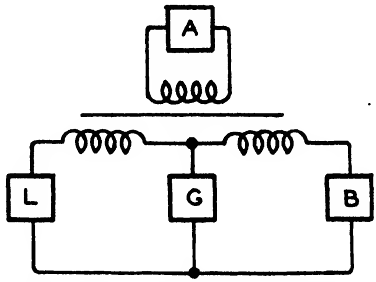


FIG. 329. PRINCIPLES OF HYBRID CIRCUIT

Hybrid Coil Bridge Circuit. The hybrid coil bridge circuit is the basis of all duplex circuits employing unidirectional amplifiers or transmission channels. It comprises a form of differential transformer, and the transmission losses in the circuit will be summarized here. In the schematic diagram, Fig. 329, the following symbols are used—

L = line impedance.
B = balance impedance.
G = input impedance of amplifier.
A = output impedance of amplifier.

The circuit is usually designed to work with line and balance impedances of 600 ohms, and to obtain this figure the line and balance are connected via transformers of a suitable ratio. If the line is very short, or if the line terminals are connected to exchange switching apparatus, a 'compromise' balance is used consisting of a 600-ohm resistance which provides a reasonable balance for any lines or apparatus which may be connected.

It can be shown that G must be half the design impedance, i.e. 300 ohms, and the turns ratio of the coil must depend upon the value of A, unity ratio being used for $A = 300$ ohms. ($A = \frac{1}{2}Lr^2$ where r is the coil ratio.)

Transmitting Direction. When a signal is received from the

line L the power divides equally between A and G, no power being received in the balance. There is thus a loss of 3·0 db. between L and A, and between L and G. The power received in G is amplified and transmitted, that received in A is merely dissipated in the anode circuit of an amplifier. G and A are of course interchangeable as transmitting and receiving channels. If, however, G were used as the receiving side, then an output transformer would be essential to match the valve anode impedance to 300 ohms. A ratio of about 4 : 1 would be necessary for a typical amplifying valve. With A used as the receiving side the output transformer ratio can be included in the hybrid coil ratio.

Receiving Direction. When L and B are approximately balanced the amplified power from A divides equally between them. There is thus a loss of 3·0 db. between A and L and between A and B.

Singing Point. When there is an unbalance between L and B, part of the power received from A finds its way into G, and the ratio of this power can be shown to be—

$$6 \text{ db.} + 20 \log_{10}\left(\frac{L+B}{L-B}\right) \quad . \quad . \quad (98)$$

The second quantity is termed the *singing point*, and if 1·0 db. is allowed for losses in the hybrid coil, the loss across the hybrid coil from A to G is approximately

$$7{\cdot}0 \text{ db.} + \text{singing point} \quad . \quad . \quad . \quad (99)$$

The actual voltage produced across G by an e.m.f. in series with A is

$$(E/4r) \,.\, (L - B)/(L + B) \quad . \quad . \quad . \quad (100)$$

where r is the coil ratio.

It is interesting to note that the expression for singing point is identical with that obtained in Chapter XIV (equation 39*b*), for reflected voltage. Accordingly, singing point can be defined as the loss corresponding to the reflection coefficient of two lines, or a line and balance network, joined together. It can also be defined as the loss corresponding to the ratio between power transmitted to a line to that returned to the sending end by reflections from irregularities. The terms *balance attenuation* and *return loss* are sometimes used.

From these considerations it is easy to see the truth of equations (98) and (99) by the following reasoning. First, power from A divides between L and B, loss 3·0 db.; second, voltage appears at the line terminals corresponding to the reflection coefficient of L and B, i.e. singing point; third, the reflected voltage divides between A and G, loss 3·0 db. Total: 6·0 db. plus singing point plus an allowance for loss in the transformer.

If the balance matches the characteristic impedance of a line which cannot be regarded as infinite, then the singing point or return loss is obviously twice the attenuation length of the line, plus the loss corresponding to the terminal reflection at the far end of the line. With the line open or short-circuited at the distant end the best possible singing point is therefore twice the attenuation length of the line.

Repeater Gain. The ratio of the power supplied to the power delivered by an amplifier or repeater, expressed in decibels, is known as the *gain*. It can be regarded as a negative attenuation.

If the gain of the amplifier portion of a two-wire repeater is μ db. then the gain of the repeater which is inserted in the line must be $(\mu - 6)$ db., not reckoning transformer losses, because there is a 3·0 db. loss on the input side and a 3·0 db. loss on the output side as has been shown in the previous section.

Repeater Stability. In a single-valve two-wire repeater the path round which oscillation might take place includes the amplifier and the hybrid coil bridge circuit. For oscillation to occur two conditions must be satisfied in this path—

(*a*) The gains must equal or exceed the losses, or

$$\begin{aligned} \mu &= \text{singing point} + 6 \text{ db.} \\ &= \text{gain} + 6 \text{ db. (by equation (98).)} \end{aligned}$$

(*b*) The total phase change must be a multiple of 2π.

Therefore the circuit is unstable when repeater gain equals singing point.

By *margin of stability* is meant the difference between the gain of the repeater in the normal working condition and the gain required to produce instability. Thus if a circuit has a total attenuation of 30 db. and the repeaters give a total gain of 27 db., the transmission equivalent (t.e.) of the circuit is

3·0 db.; then if the circuit becomes unstable when the transmission equivalent is reduced to 1.0 db., the margin of stability is 2·0 db.

Just before instability occurs serious distortion of speech takes place, and a margin of about 2·0 db. must therefore be allowed at each repeater.

Two-valve Two-wire Repeater. For satisfactory operation the single valve repeater must be connected between the lines

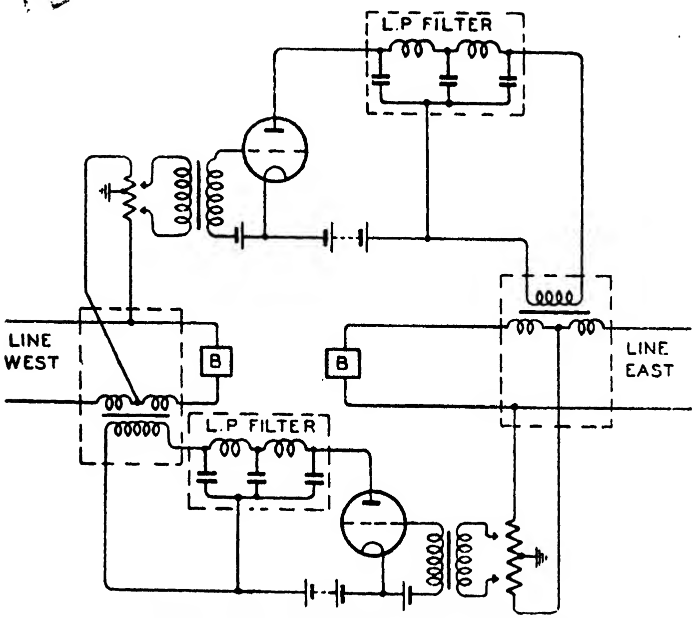


FIG. 330. TWO-WIRE TWO-VALVE REPEATER

which balance each other. This requires (*a*) that the lines have the same impedance characteristics and are therefore of the same type, and (*b*) that the lines be approximately equal in length.

These requirements constitute serious practical disadvantages, and this type of repeater has therefore been entirely superseded by the 2-valve type of circuit shown in Fig. 330. The term *two-wire repeater* is therefore used to mean the two-valve type of circuit.

Separate amplifiers are used for each direction of transmission, and the east and west lines are balanced individually

by means of networks which will be found described in detail on p. 443.

As in the single-valve circuit, the repeater gain equals amplifier gain less 6 db., but in this case one division of power occurs in one bridge circuit and the second division occurs in the second bridge circuit.

The oscillation path includes two amplifiers and two bridge circuits; therefore instability will occur when the average

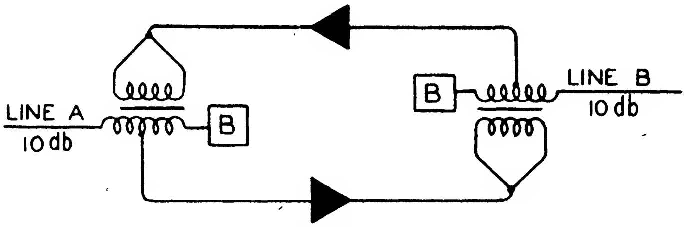


FIG. 331. LINE WITH TWO-WIRE REPEATER

repeater gain equals the average of the two singing points. Thus if one line is short and has a poor singing point, the other line may have a good singing point and enable a reasonable gain to be obtained.

With coil-loaded lines the impedance-frequency characteristics show increasingly large irregularities as the frequency is increased towards the cut-off. (See Fig. 306.) Now the balance networks have smooth impedance characteristics, and thus the singing points fall rapidly at the frequencies near the cut-off. To avoid instability at these frequencies low pass filters are introduced into the amplifiers, having a critical frequency just below the cut-off of the cable. The circuit shown in Fig. 330 includes a two section low pass filter in each amplifier. The theory of filters has been given in Chapter XVI.

Limitations of Two-wire Repeaters. Consider a line of about 20 db. attenuation with a two-wire repeater located about midway between the ends A and B. (See Fig. 331.)

The ends A and B must be available for extension to any type of line or apparatus and the most stringent conditions for stability which must be catered for are open circuit and short circuit, i.e. when total reflection takes place from the ends. Now it has already been shown that the best singing point which it is theoretically possible to obtain with total

reflection from the ends is equal to twice the attenuation length of the line.

Also, the maximum average repeater gain obtainable before instability occurs is equal to the two singing points. It follows therefore that under the best theoretical conditions the circuit will become unstable when the transmission equivalent in both directions is reduced to zero.

It is not possible in practice to obtain zero transmission equivalent on a circuit before instability occurs. Irregularities along a line cause partial reflections and reduce the balance attenuation. These reflections are caused by the irregularities in the impedance characteristics which cannot be simulated in the balance networks. The circuit will therefore sing at something worse than zero transmission equivalent.

When there are several repeaters in a circuit the reflected currents or echo currents come partly from the distant end of the line via the intermediate repeaters, partly from line irregularities, and partly from impedance mis-matches between the repeaters and the lines.

When repeater gain is increased, serious distortion of speech occurs as the unstable condition is approached, and for this reason a margin of stability or singing margin of 1·5 to 2·0 db. must be allowed. The circuit in Fig. 331 must therefore have a transmission equivalent of several decibels. Similarly if there are several sections of line and several repeaters, a margin of stability must be allowed at each repeater. Thus in practice a line with, say, four repeaters cannot have a transmission equivalent better than about 7 or 8 decibels.

Four-wire Repeatered Circuits. The limitations of two-wire repeatered circuits for long lines can be avoided by using separate transmitting and receiving channels throughout. Referring to the schematic diagram of a two-wire repeater, Fig. 331, if the repeater be stretched out so that the hybrid coils are located at the ends of the circuit the transmitting amplifier becomes a transmitting line and amplifier, and the receiving amplifier becomes a receiving line and amplifier, the number of amplifiers depending upon the total attenuation of the lines. Thus four wires, two lines, are used and no line balances are necessary. At the termination of the circuit only 'compromise' balances are required, to balance approximately

any telephone apparatus or local lines which may be connected to the circuit. A schematic diagram of a circuit is shown in Fig. 332.

If the four-wire circuit is regarded as a stretched out two-wire repeater with infinitely short lines, it will be evident from what has been said about the stability of repeaters that this four-wire circuit will become unstable when the end-to-end transmission

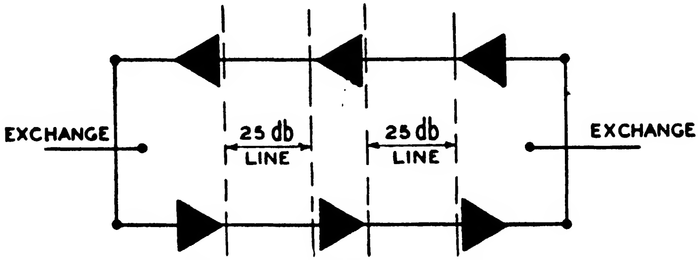


FIG. 332. SCHEMATIC DIAGRAM OF A FOUR-WIRE CIRCUIT

equivalent is made zero, since the singing points are zero. A margin of stability is of course necessary, and the transmission equivalent of four-wire circuits is usually adjusted to 3 db. In the case of two-wire repeaters the maximum spacing in decibels of line attenuation between the repeaters depends upon the singing points which can be expected from the balances. For four-wire circuits, however, as much amplification as is desired can be obtained from the unidirectional amplifiers using two stages of amplification if necessary and the maximum spacing is governed entirely by cross-talk considerations. The power level must not fall so low between amplifiers that it becomes comparable with the power level of the cross-talk from other circuits, and the output power level from the amplifiers must not be so high as to cause serious cross-talk to other circuits. To minimize cross-talk the power levels should be limited to a range of about 30 db. between repeater input and repeater output, and further all circuits in the same cable should be adjusted to approximately the same output and input power levels. If separate groups of wires, or better still separate cables, can be used for transmitting and receiving channels, cross-talk can be further reduced because it will then only take place between similar power levels, whereas it would otherwise take place from high output level on one circuit to low input

level on another circuit. There are also other advantages from a cable balancing point of view.

A circuit may also be made up partly four-wire and partly two-wire. In this case the four-wire section being equivalent to a two-wire repeater may be given a negative transmission

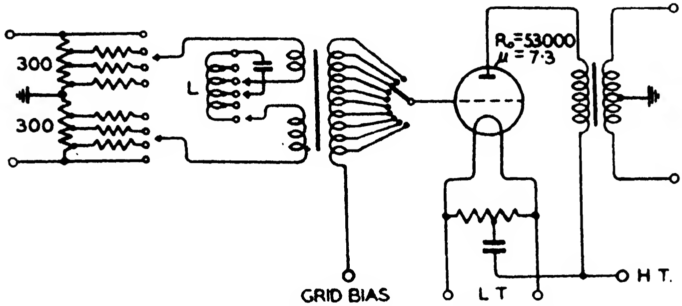


FIG. 333. SINGLE-STAGE FOUR-WIRE REPEATER

equivalent, i.e. give a gain to the circuit, depending upon the singing point of the two-wire section and its balance.

Four-wire Repeaters. A four-wire repeater consists of two unidirectional amplifiers. The two amplifiers themselves are quite distinct, although a common filament circuit may be used.

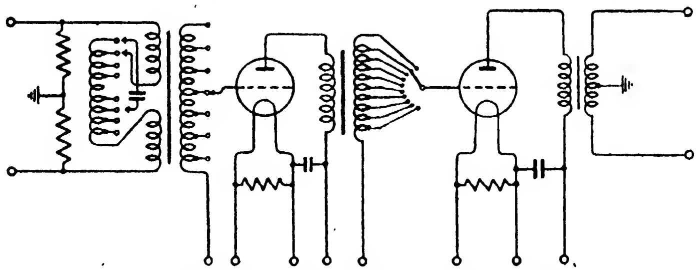


FIG. 334. TWO-STAGE FOUR-WIRE REPEATER

Both single- and double-stage repeaters are in general use depending upon the gain required. The circuit of a single-stage repeater is shown in Fig. 333. The valve has an amplification factor of 7·3, and an internal impedance of 5 300 ohms. The input and output impedances of the repeater are 600 ohms. Gain control is obtained partly by tappings on the input transformer (fine adjustment), and partly on a 600-ohm potentiometer (coarse adjustment). The inductance coil and condenser

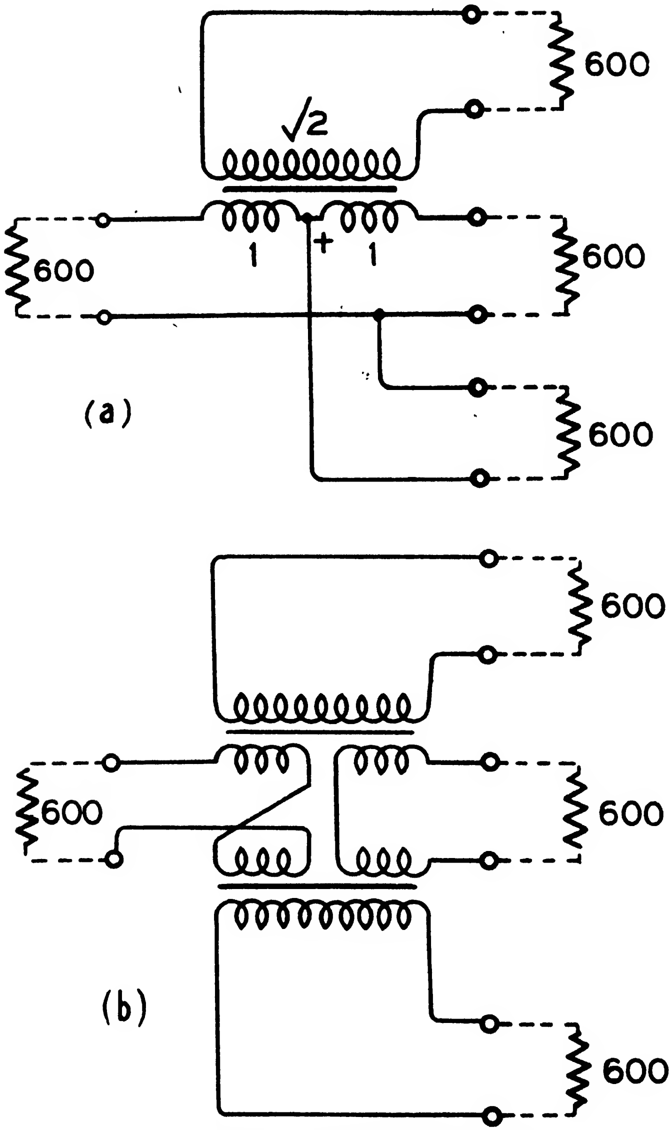


FIG. 335. FOUR-WIRE TERMINATIONS

combination in series with the primary of the input transformer is for equalization of attenuation at the higher frequencies.

A two-stage repeater circuit is shown in Fig. 334. In this circuit gain control is obtained partly at the input transformer and partly at the inter-valve transformer.

Four-wire Terminations. Four-wire terminations are simply hybrid coil bridge circuits which have already been described

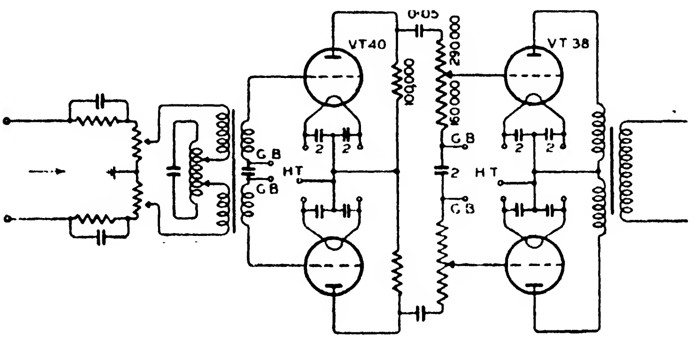


FIG. 336. TWO-STAGE PUSH-PULL REPEATER

in detail. When not fitted as an integral part of a repeater the transformer ratios are usually arranged so that the network has 600 ohms impedance from all points. (See (*a*), Fig. 335.)

Another form of this circuit employing two transformers is shown at (*b*), Fig. 335.

Push-pull Repeaters. A repeater circuit capable of handling a greater power and at the same time giving much greater freedom from harmonic distortion is shown in Fig. 336.

For each stage of amplification two valves are used working in parallel. The signals applied to these valves are 180° out of phase with respect to one another, i.e. when the signal to one valve is causing an increase of anode current the signal to the other is causing a decrease of anode current. The effect of non-linearity in valve characteristics is fully dealt with in Chapter XVIII on "Carrier Working," but it can be said here that non-linearity causes harmonics to be produced in the amplified signal, principally second harmonics. It is shown in Chapter XVIII that if both valves of a push-pull stage have exactly the same characteristics, then the second harmonic and all other even harmonics are eliminated entirely. In practice

valves have not exactly similar characteristics, but a very considerable reduction in second harmonic can be obtained. If a push-pull stage is seriously overloaded, third harmonic may become prominent.

The effect of harmonic distortion on the syllable articulation efficiency of a circuit is very slight, and is probably entirely masked by the considerable harmonic distortion introduced by ordinary telephone transmitters and receivers. Push-pull repeaters or some form of harmonic compensator are only used on circuits to carry music transmissions or carrier telephony. In the latter case harmonic distortion gives rise to inter-modulation cross-talk.

Echo Effects.—Trunk lines are provided at each end with compromise balances, consisting of 600-ohm resistance, to give a reasonable balance with any local lines or apparatus which may be connected. The impedance connected to the trunk circuit may vary from a few hundred ohms in the case of aerial lines to nearly 2 000 ohms in the case of heavy loaded cable circuits. The phase-angle of the impedance may vary from 45° negative with unloaded cable circuits to nearly 45° positive for a telephone instrument. Considering the whole frequency range transmitted the possible impedance variations will be even greater. A compromise balance can therefore only be very approximate and considerable reflection will occur.

If the transmission equivalent of the trunk circuit is good, say only a few decibels worse than zero, the reflections will cause a person using a telephone at one end of the circuit to hear his own voice in his receiver. The effect of this on the speaker must be considered separately for long lines and short lines. With short lines the effect is the same as the side-tone produced in a telephone by direct transmission from transmitter to receiver. A certain amount of side-tone is essential. Its effect is mainly psychological: when it is entirely absent the telephone user thinks that the line is dead, whilst if it is excessive he tends to lower his voice and reduce the sending equivalent.

On long lines the echo currents arrive at the transmitting telephone after an appreciable interval of time. The delay interval will be twice the transmission time of the circuit. The echo time of a 1.000 mile circuit in medium-heavy loaded cable

for example will be about $\frac{1}{5}$ sec. The speaker will hear what is apparently an ordinary acoustic echo which may be so disturbing as to make conversation difficult or impossible.

With high grade circuits the second and subsequent reflections may be heard at both ends of the connection.

On long circuits of high transmission efficiency it is therefore necessary to provide echo suppressing devices. It is the practice

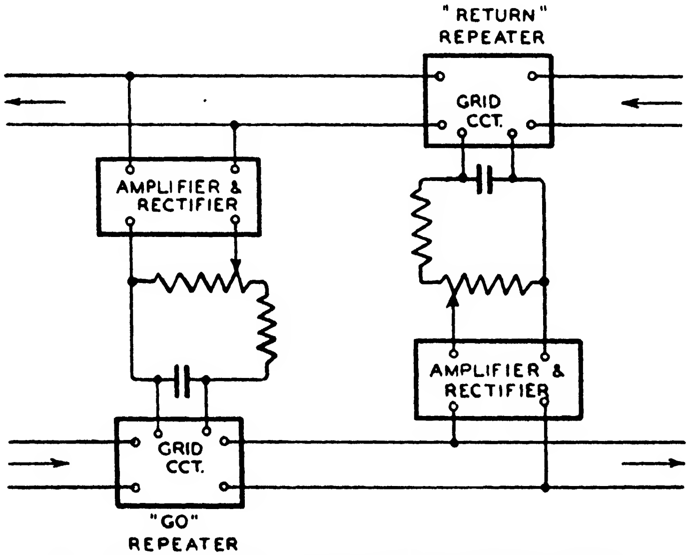


FIG. 337. SCHEMATIC DIAGRAM OF AN ECHO-SUPPRESSOR

of the British Post Office to fit echo suppressors on all long distance trunk circuits having a transmission equivalent of less than 3·0 db.

Echo Suppressors. An echo suppressor is a voice-operated device associated with a repeater which will make the circuit unidirectional whilst transmitting speech. Thus when transmitting in the GO direction the RETURN channel is rendered inoperative, and vice versa. Fig. 337 shows the schematic arrangement of a valve type suppressor associated with a four-wire repeater. A circuit diagram is shown in Fig. 344.

The operation of the valve-type suppressor is briefly as follows. A portion of the amplified signal is taken from the output of the repeater in one channel amplified and rectified and applied as an additional negative grid bias to one of the

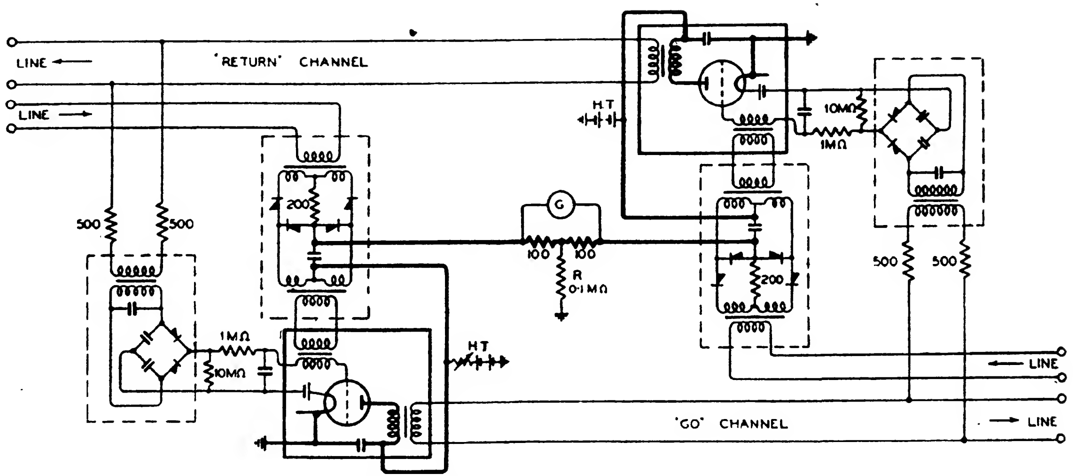


FIG. 338. VALVELESS DIFFERENTIAL ECHO-SUPPRESSOR

valves in the repeater of the other channel. This additional bias is sufficient to reduce the repeater gain by 10 to 20 db. and thus virtually close the channel. For satisfactory operation the circuit must be designed and adjusted so that—

(*a*) The sensitivity, i.e. the signal voltage required to produce suppression, is adequate for any signal level which may be

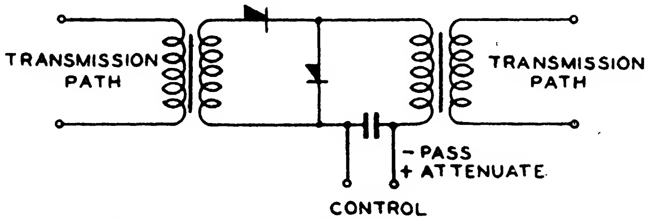


Fig. 339. Variable Attenuation Network

transmitted, whilst at the same time it must not be so sensitive that it will respond to noise on the circuit. The noise will

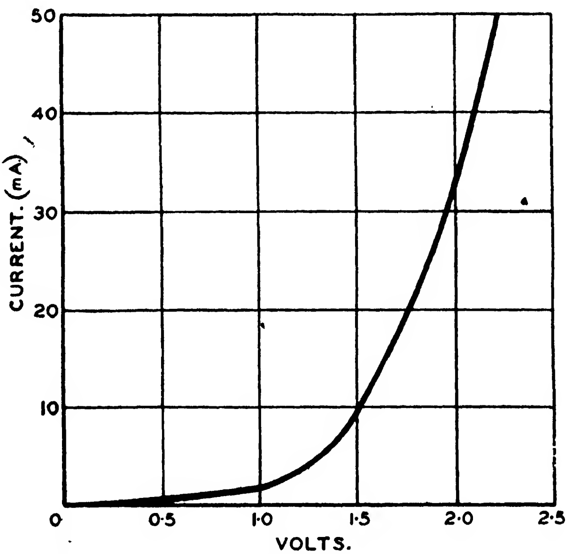


Fig. 340. Voltage-current Curve of Copper-copper Oxide Rectifier

originate partly as interference (cross-talk) and partly from room noise where the telephones are located.

(*b*) The suppressor must be arranged with a hang-over time or delay in restoring to normal after a signal in order to cut off

the echo coming from the other end of the circuit, and to cover short intervals between syllables. The hang-over is arranged by means of the condenser and resistance. The time is usually about 200 msec.

Another type, known as the *valveless differential echo suppressor*, is shown in Fig. 338.

In this circuit suppression is obtained by means of variable

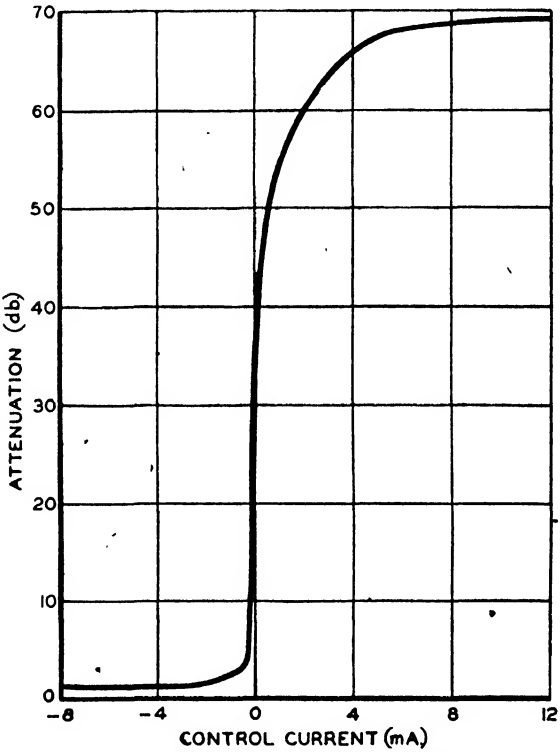


FIG. 341 (*a*). CHARACTERISTIC OF BALANCED ATTENUATION NETWORK

attenuation networks incorporating copper-copper oxide dry plate rectifiers. The simplest form of such a network is shown in Fig. 339.

The rectifiers are arranged so that with a control current in one direction the series rectifier presents a high resistance whilst the shunt rectifier presents a low resistance, thus causing the complete network to give a high attenuation. With a control current in the opposite direction the condition of the rectifiers

is reversed, and there is only a small attenuation. The d.c. characteristic of a typical rectifier is shown in Fig. 340. A balanced form of attenuation network is used in the echo suppressor, and Fig. 341 shows attenuation plotted against control current for these networks.

The action of the suppressor is as follows. When transmitting in the GO direction, for example, part of the amplified signal is rectified by a double-wave rectifier using dry-plate rectifiers and used to produce a positive grid bias for the repeater in the return

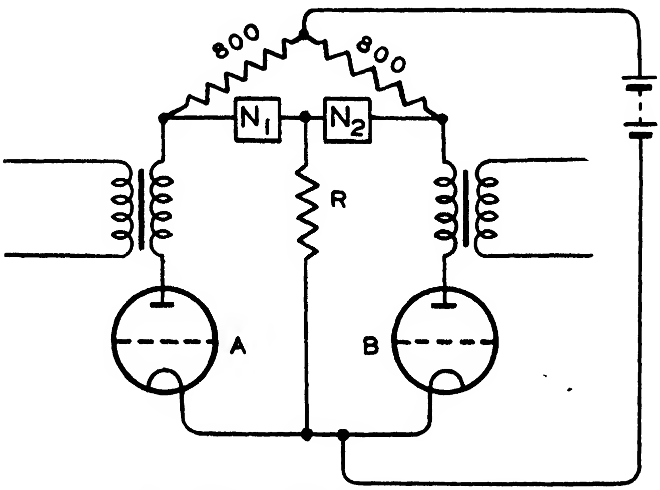


FIG. 341 (b). ANODE BRIDGE CIRCUIT

channel. This positive bias causes a larger increase in anode current to the RETURN amplifier. The anode circuits are arranged as a bridge circuit with the two attenuating network control paths in place of a galvanometer. (See Fig. 342.) A galvanometer may actually be included to show the working of the suppressors. When the return amplifier takes an increase of anode current the bridge becomes unbalanced, and a current flows through the control networks. The RETURN network is caused to give a high attenuation and the GO network has its small initial loss reduced to the minimum. The leak resistance *R* (Fig. 338) is to provide a small control current through both networks in the idle condition. The working point with this current is indicated on Fig. 341. The suppressor operates in a similar manner when transmitting over the return channel.

Compandor. In spite of all the precautions taken in balancing the underground cable pairs, and in spacing the loading coils and repeater equipment, crosstalk may still occur to an extent which greatly depreciates the value of the circuit, especially on long submarine cable channels. A device, termed a "compandor," may be employed in such a case, and operates as follows. A "compressor" unit is inserted at the transmitting end of each GO pair, and an "expander" unit at the

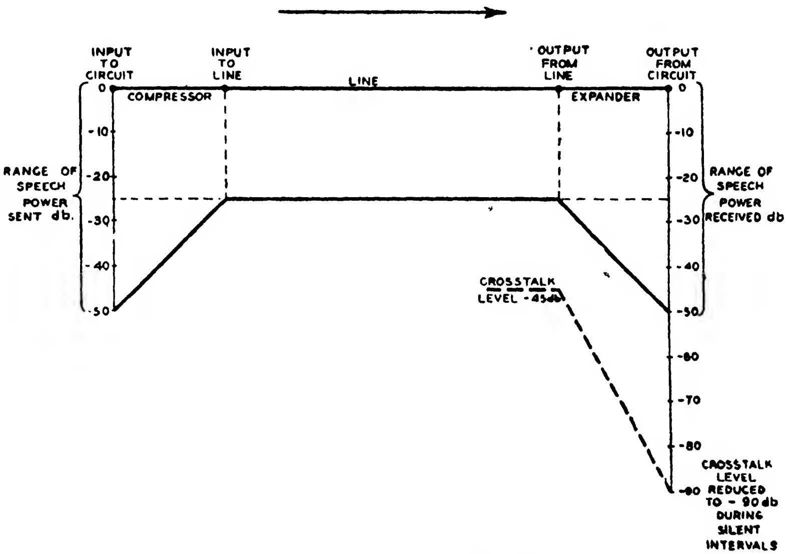


FIG. 342. PRINCIPLE OF COMPANDOR

terminal of the RETURN pair. Each unit consists of an amplifier, the gain of which is controlled by the level of the applied signal. At the "compressor" end, a signal at peak level (determined by voltage limiter or other means) is transmitted to line unchanged in magnitude, whilst a signal of relative strength Ndb. less is transmitted at a level of $N/2$ db., i.e. the normal range in db. of the outgoing signals is compressed to one-half of its initial value before transmission. At the receiving end, the "expander" operates with a reciprocal action. As before, peak level signals are unaffected in level, but a signal of relative level Ndb. is attenuated to a level $2N$db., and thus the received range of signal level is expanded to its original compass. The value of this procedure will now be apparent,

since cross-talk at the receiving end, which might be at a level of 45db. relative to the peak signals in a normal termination, is reduced to a level of 90db. during silent intervals, and is virtually inaudible. The principle is illustrated graphically in Fig. 342.

Battery Supply and Grid Priming Circuits. In telephone

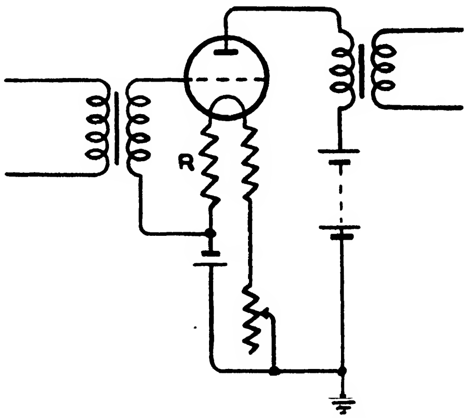


FIG. 343. PRINCIPLE OF AUTO-GRID PRIMING

repeater stations power for the valves is obtained from secondary cells.

A 22-volt 'A' battery with positive connected to earth is provided for the filament circuits. Usually four valves are connected in series.

A 130-volt or 150-volt 'B' battery with negative to earth is provided for the anode circuits. Originally small 'C' batteries were provided for biasing the grid circuits, but *auto-grid priming* is now almost universally used.

The principle of auto-grid priming is shown in Fig. 343. The grid bias is the voltage across *R* due to the filament and anode currents.

A complete filament circuit for a two-stage four-wire repeater and an associated valve type echo suppressor is shown in Fig. 344.

Smaller amplifier installations are operated direct from electric supply mains with secondary cell batteries to operate the amplifiers for several hours in case of failure of the mains supply. A float charging system may be employed or an

automatic change-over scheme whereby the standby batteries are connected to the amplifiers when failure of the mains supply occurs. A low voltage filament supply is used (4 volts at the filament terminals) all valves being in parallel.

With the float charging scheme the power from the mains is rectified but not smoothed, whilst with the auto-changeover

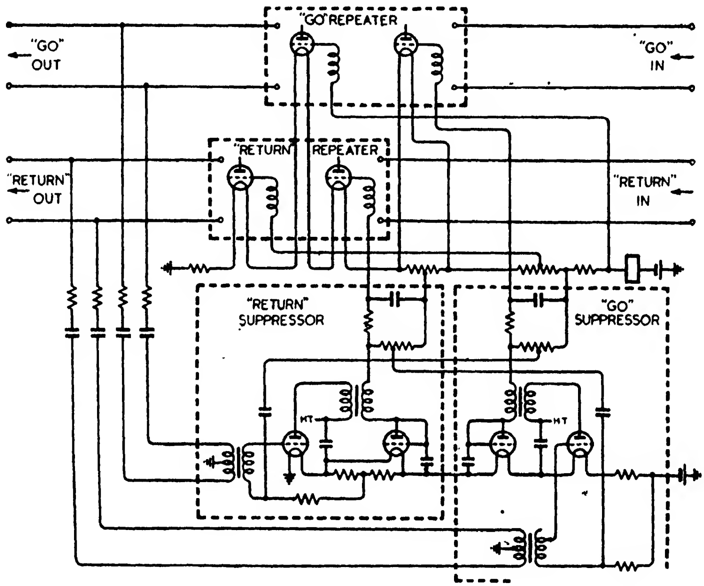


FIG. 344. FILAMENT AND GRID PRIMING CIRCUIT OF FOUR-WIRE REPEATER WITH ECHO-SUPPRESSOR

scheme alternating current at 4 volts is connected to the filaments. Special steps are therefore necessary to prevent hum at power supply frequency and its harmonics being produced in the transmission circuits.

The first step to avoid noise on the lines is to connect the negative of the anode battery to the mid-point of the filaments, which in effect is accomplished by the resistances $R_1 R_2$ shown in Fig. 345. If $R_1 = R_2$ the mean potential between anode and cathode will be a constant. Now consider the dynamic characteristics of the complete amplifying circuit and apply equation (91)

$$i_a = (1/R_a)(v_a + \mu v_g).$$

The speech circuit is completed by the condenser C_1 and in this

path, with a.c. on the filament, a voltage v_a is obtained equal to half the voltage across the filament.

Let this equal $\frac{1}{2}s$; then

$$i_a = (1/R_a)\,(\tfrac{1}{2}s + \mu v_g).$$

This represents the mains hum heard in the transmission

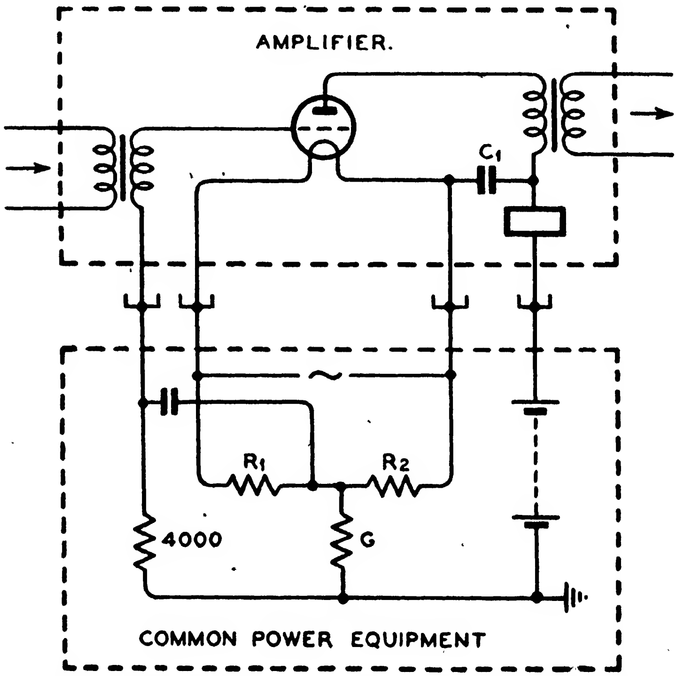


FIG. 345. AMPLIFIER WITH COMMON GRID PRIMING CIRCUIT

circuit. It can be eliminated by applying an opposite potential

$$v_g = -\,s/2\mu$$

to the grid, which is accomplished by shifting the anode return so that R_1 is reduced by R/μ and R_2 is increased by R/μ. For example, for a valve with amplification factor of $\mu = 9$ the following resistances will be suitable.

$$R_1 = 1{\cdot}6 \text{ ohms.}$$

$$R_2 = 2{\cdot}0 \text{ ohms.}$$

The value of G must be adjusted to give the required grid bias. As this resistance is common to a number of amplifiers the

4 000-ohm resistance and 4-μF. condenser are included to prevent overhearing between circuits.

Balance Networks. First consider coil-loaded lines; a typical impedance curve for a line with a half-section termination is shown in Fig. 306. The general form of the impedance curves —effective resistance and reactance—for other values of end

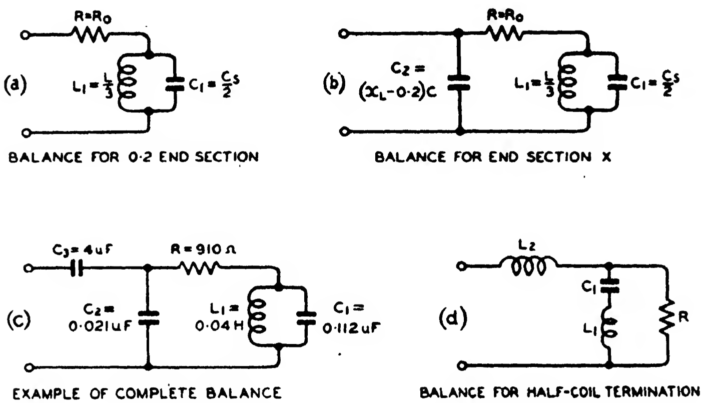


FIG 346. BALANCES FOR COIL-LOADED LINES

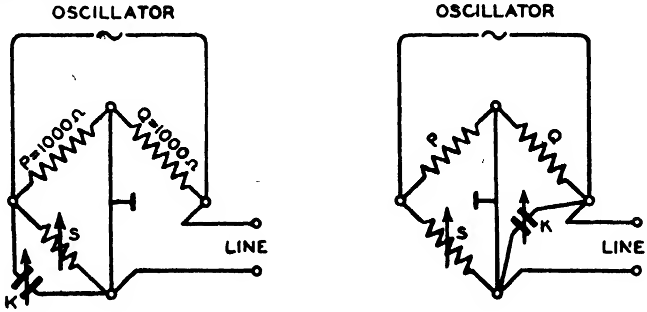
section are shown in Fig. 309. It is seen that with an end section of 0·2 of a loading coil section the effective resistance is reasonably constant at $R_o = \sqrt{(L/C_s)}$, whilst the reactance rises with frequency.

A reasonable balance for a 0·2 section can be obtained from a resistance R_o, in series with a parallel tuned circuit to give the rising reactance curve. (See (*a*), Fig. 346.) It is found in practice that an inductance of about one-third the loading coil inductance and a condenser C_1 of about half the loading section capacitance is found suitable. When the cable has an end section longer than $0{\cdot}2S$ it is obvious that an additional condenser C_2 (see Fig. 346) will be required in the balance; roughly equal to the extra capacitance of the end section, i.e. $(x - 0{\cdot}2)$ C_3.

At very low frequencies the impedance of the cable has a large negative reactance, and the balance can often be improved by the addition of a series condenser C_3 of large capacitance. A typical complete balance is shown at (*c*), Fig. 346. With a half-coil termination the impedance will be

the inverse of the half-section impedance, and the inverse balance network will therefore be required. (See Fig. 346 (*d*).)

The above treatment is based on the ideal filter theory of the previous chapter, and some modification is required in practice. The higher the attenuation of the line the more is the modification required. In addition, actual lines have impedance irregularities, and the balance must be adjusted to give an



(a) FOR NEGATIVE ANGLES (b) FOR POSITIVE ANGLES

FIG. 347. IMPEDANCE BRIDGE

impedance curve which will be the mean of the cable impedance, in order to obtain the best possible singing point.

To obtain an accurate balance impedance measurements are made, and the elements of the network adjusted carefully. The bridge circuit used for the impedance measurements is shown in Fig. 347.

Since the ratio arms P and Q are equal, the bridge will be balanced when the combined impedance of S and K equals the line impedance in both magnitude and angle. It follows then that the admittances will be equal and

$$\left.\begin{aligned} &\text{Conductance} \quad . &&= \frac{1}{S} \\ &\text{Susceptance} &&= \pm \omega K \\ \text{from which} \\ &\text{Effective resistance} &&= \frac{S}{1 + S^2\omega^2K^2} \quad . \\ &\text{Reactance} &&= \pm \frac{S^2\omega K}{1 + S^2\omega^2K^2} \end{aligned}\right\} \quad . \ (101)$$

The reactance is positive or negative according to whether the condenser K is across the line or the resistance S. There is no need, however, to calculate effective resistance and reactance, the actual S and K reading can be plotted; the same graph being used for both line and balance. (See Fig. 349.)

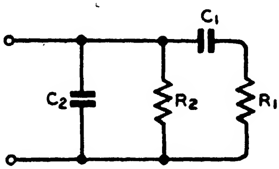


FIG. 348
BALANCE FOR UNLOADED AND CONTINUOUSLY LOADED LINES

The operations in making up a balance are briefly as follows—

(1) Measure the line impedance and plot the S and K values.

(2) Draw mean curves giving the readings for the required balance.

(3) R is found from the minimum value of the required S curve.

(4) L is made equal to one-third the loading coil inductance as near as possible with the inductance coils available.

(5) C_1 is adjusted to give a suitable S curve up to about 0·75 of the cut-off frequency.

(6) C_2 is adjusted to give suitable K readings over the main frequency band.

(7) C_3 is adjusted to give suitable K readings at low frequencies.

The above operations are carried out with the aid of a variable resistance and condensers, components of fixed values being obtained when the final values have been determined.

Balances for aerial lines, unloaded cables, and continuously loaded cable circuits are usually made from a network of the form shown in Fig. 348. The preparation of this type of balance is somewhat more difficult than the loaded cable type. It is usual to find the values of the elements by calculation. Typical values for a 40 lb. unloaded cable circuit are—

$$C_1 = 0{\cdot}516\ \mu F.$$
$$C_2 = 0{\cdot}19\ \mu\text{F}.$$
$$R_1 = 450 \text{ ohms}$$
$$R_2 = 1\ 200 \text{ ohms}$$

Attenuation 'Equalization' by Repeater Gain Adjustment. A certain amount of compensation for the increased attenuations of loaded circuits at the higher frequencies can be effected by

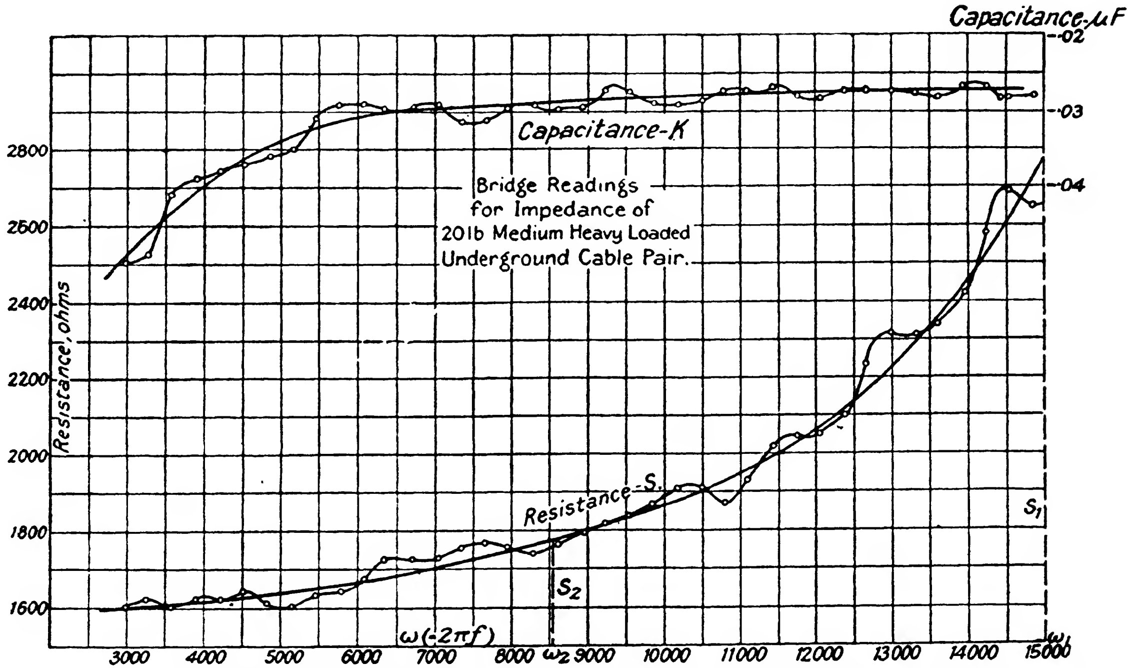


FIG. 349. BRIDGE READINGS FOR IMPEDANCE OF UNDERGROUND CABLE PAIR

giving the repeaters increased gain at the higher frequencies. The most usual way of arranging this is by means of a tuned

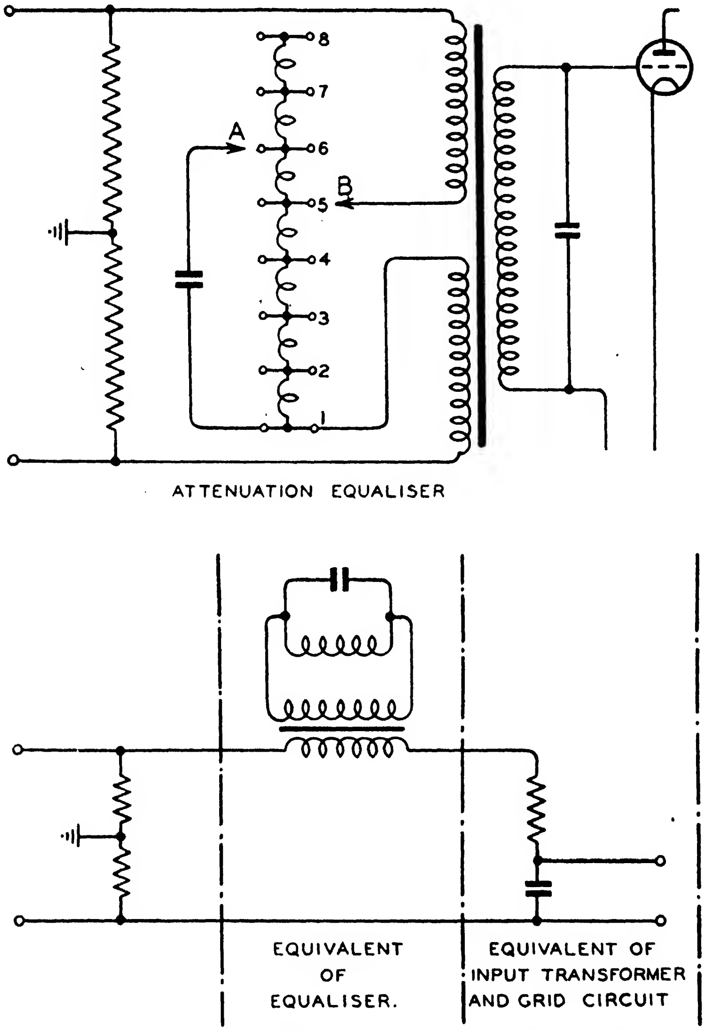


Fig. 350. Attenuation Equalization Circuit and its Equivalent

circuit in series with the input transformer as shown in the repeater circuits Figs. 333 and 334.

It will be seen from Fig. 350 that this arrangement is in effect

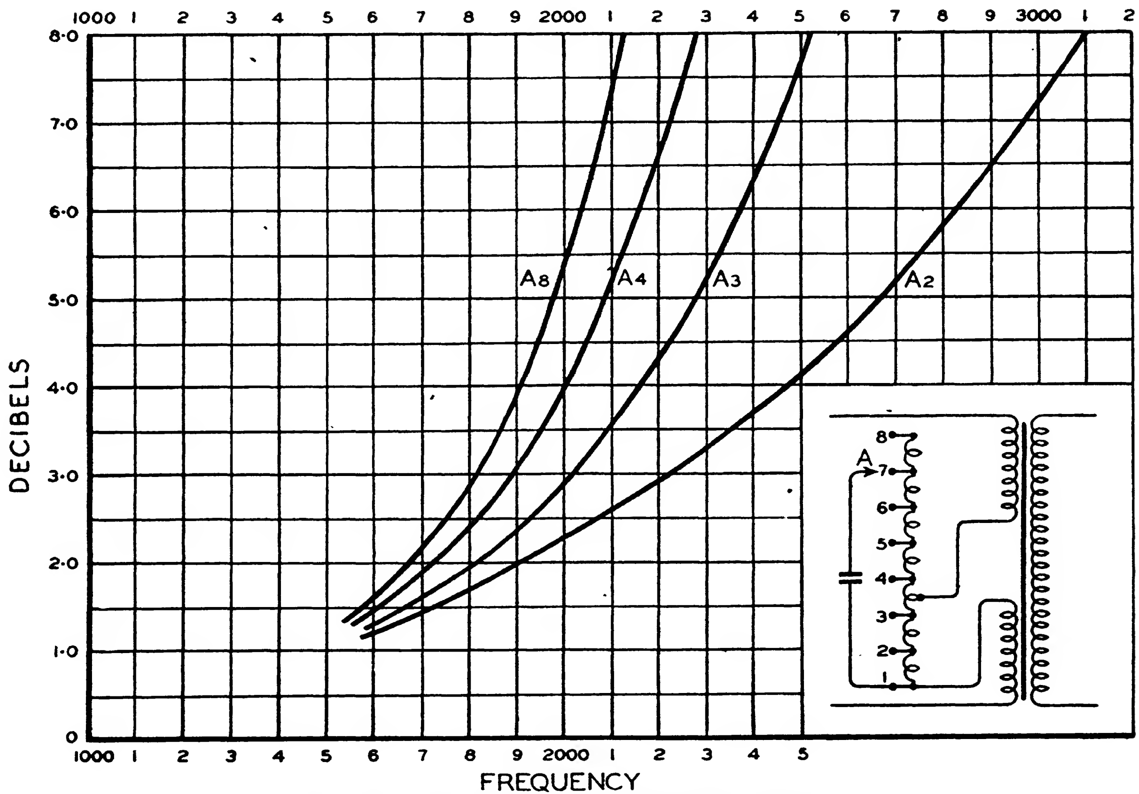
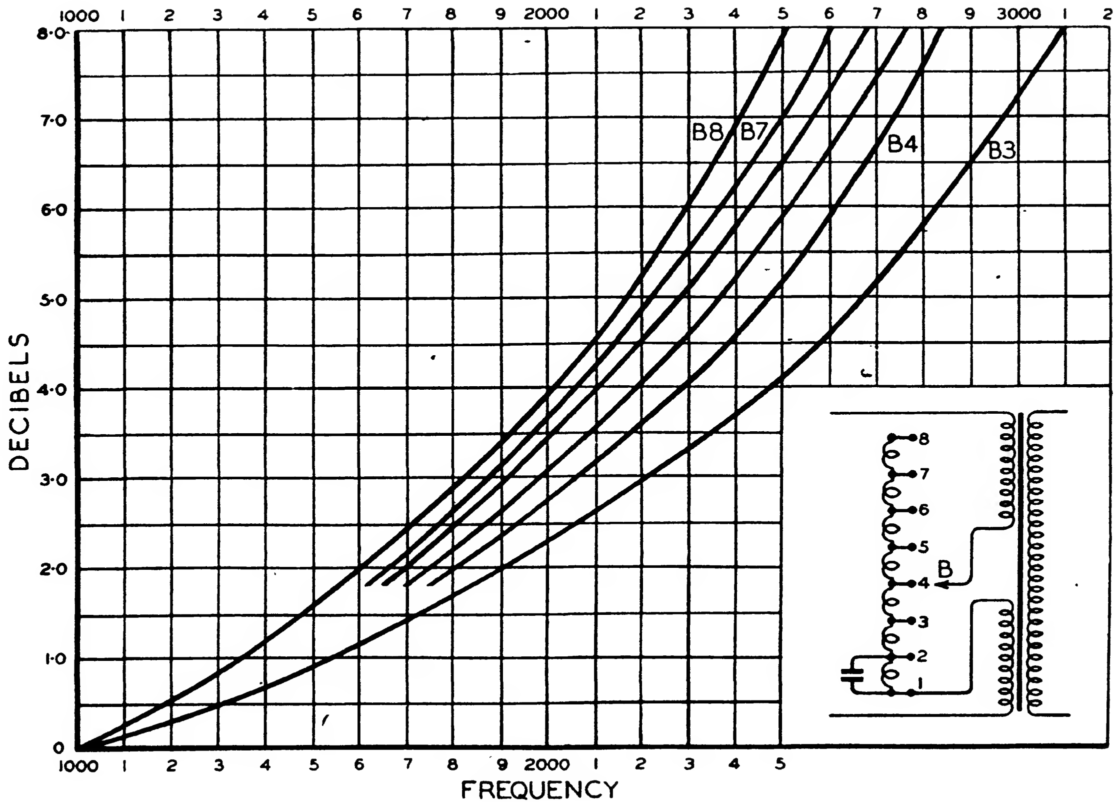


Fig. 351. Equalization with Condenser Tappings


DECIBELS
FREQUENCY
B3
B4
B7
B8
B
1
2
3
4
5
6
7
8

a rejector circuit joined in series by a transformer. This is because the tapped inductance forms part of the tuned circuit and at the same time constitutes an auto-transformer. The tuned circuit has a reactance

$$jX = \omega L/(1 - \omega^2 LC)$$
$$= \frac{\omega L}{1 - (\omega/\omega_c)^2},$$

where ω_c is the resonant frequency. Below ω_c the reactance is positive and increasing. The grid circuit gives a negatively reactive load and a condenser $C_2 \doteqdot 0{\cdot}00035\mu$F. may be added as shown. It will be seen that the addition of the equalizer with its positive reactance will make the amplifier give an increased gain as the critical frequency at which the grid circuit and equalizer resonate is approached. The condenser tapping controls the resonant frequency of the equalizer, and the inductance tapping controls the auto-transformer ratio. Figs. 351 and 352 show the way in which repeater gain is affected by condenser tappings and inductance tappings respectively.

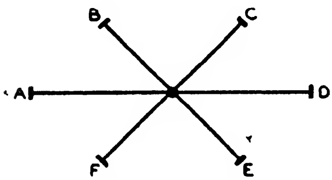


FIG. 353. OMNIBUS CIRCUIT

Omnibus Repeaters. It is sometimes necessary to join a number of lines together at one point to form an omnibus circuit. (See Fig. 353.) The transmission loss between any two telephones will be the sum of the two line losses plus reflection and division of power losses.

Suppose there are N lines each of impedance Z, then each line will be terminated with an impedance $(N - 1)Z$ giving a reflection loss

$$10 \log_{10} \frac{[(N-1)Z + Z]^2}{4Z^2\,(N-1)}$$

$$= 10 \log_{10} \frac{N^2}{4\,(N-1)} \text{ (from equation (41), Chapter XIV).}$$

The power from one line divides between $(N - 1)$ lines giving a division loss—

$$10 \log_{10} (N - 1) \text{ db.}$$

Between any two telephones therefore there is a loss in decibels of

$$\text{line losses} + 10 \log_{10} (N^2/4) \quad . \quad . \quad . \quad . \quad (102)$$

For five lines this additional loss amounts to 8·0 db., and for 10 lines 14·0 db.

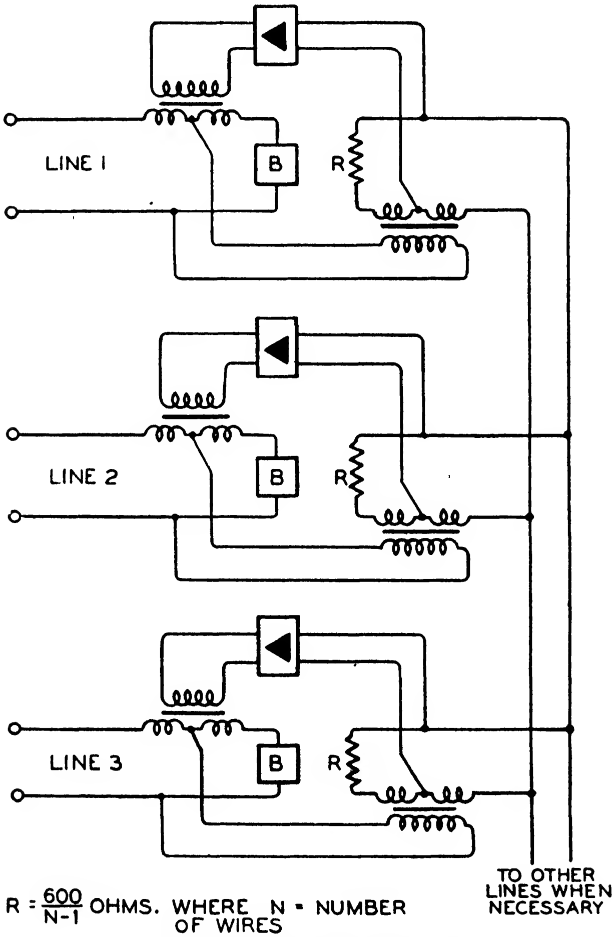


Fig. 354. Omnibus Repeater

A repeater giving amplification of the speech to each line can be arranged as shown in Fig. 354. The lines can be either two-wire or four-wire.

The Valve as an Oscillator. It has been pointed out that a

two-wire repeater will become unstable and oscillate if two conditions are fulfilled by the circuit, viz.—

(*a*) That the gains must equal or exceed the losses round the circulation path; and

(*b*) That the phase change round the path must be a multiple of 2π radians.

It is therefore obviously possible to use a valve amplifier as a generator of alternating current by arranging that sufficient

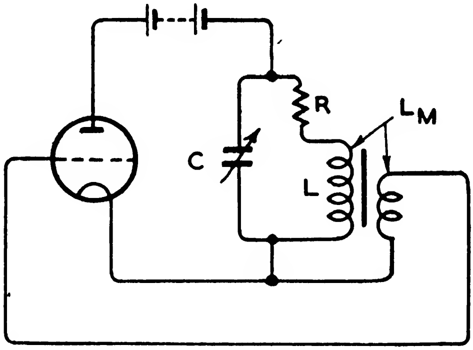


FIG. 355. OSCILLATOR CIRCUIT

voltage with the right phase is taken from the anode circuit and applied to the grid of the valve.

A simple valve oscillator in which the feed-back is obtained by mutual-inductance is shown in Fig. 355. The anode circuit is tuned to the required frequency by C and L. The resistance of the inductance coil is represented by R. The conditions under which this particular circuit will oscillate can be determined as follows—

Let i be the current in the tuned circuit; then the potential applied to the grid will be

$$v_g = \omega L_M i.$$

From equation (94) the power in this circuit (impedance Z) is

$$v_g{}^2\mu^2 Z/(Z + R_a)^2$$

The amplifier will be unstable if this is equal to or greater than the power dissipated in R; i.e., if

$$v_g{}^2\mu^2 Z/(R_a + Z)^2 \geqq i^2 R \quad . \quad . \quad . \quad (a)$$

At the resonant frequency

$$\omega^2 = 1/LC,$$

and $$Z = L/CR + 1/j\omega C \doteqdot L/CR.$$

Substituting for v_g, ω and Z in (a)

$$\frac{L_M{}^2\mu^2 i^2}{C^2R(L/CR + R_a)^2} \gtrless i^2R$$

from which $$(L_M\mu - L)/CR_a \gtrless R \quad . \quad . \quad . \quad (103)$$

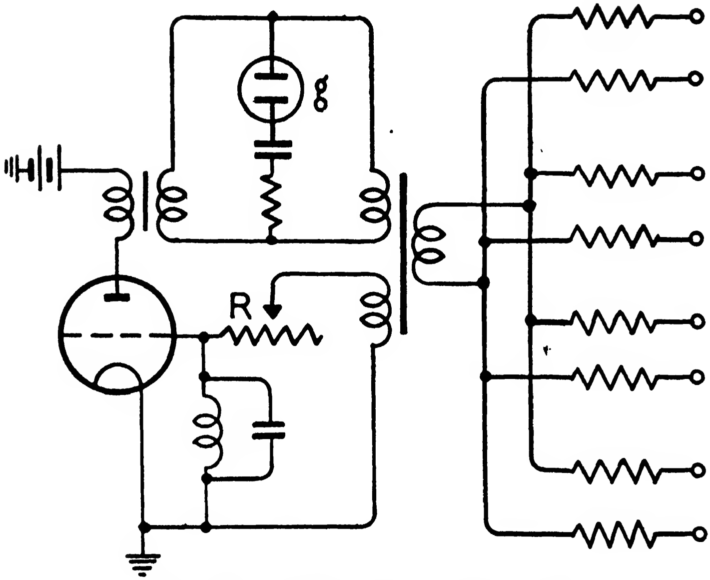


FIG. 356. CONSTANT OUTPUT OSCILLATOR

Note that once the circuit is unstable oscillation will commence, because movement of the electrons in the valve will be sufficient to give an initial impulse.

Oscillators are used principally for supplying carrier current and testing current. For the former purpose the output must be free from harmonics, and the frequency must be stable within a few cycles per second. For the latter purpose many types of oscillator are used which can be divided into three main classes—

(a) Oscillator of which the frequency can be varied, usually between about 50 and 20 000 per sec.

(b) Oscillators giving three or four frequencies according to the setting of a switch controlling the capacitance in the tuned circuit.

(c) Oscillators designed to give one frequency only (usually 800 per sec.) for routine transmission measurements.

For the last type accuracy of the frequency or purity of the tone is not so important a point as ease of operation with the minimum of controls. The usual power used for testing transmission equivalents is 1 mW. and for rapid check measuring purposes an oscillator has been designed which gives a constant output of 1 mW. without any need for verification. The circuit is shown in Fig. 356. The grid circuit is tuned to the required frequency and it will be seen that between the anode and output transformer a neon discharge lamp is connected across the path. This lamp limits the voltage and the transformers are designed so that the output voltage which is a constant is sufficient to deliver 1 mW. into 600 ohms at each of the pairs of output terminals. The resistance *R* limits the voltage so that the lamp just flashes over under the worst conditions, i.e. with all four outputs in use and minimum voltage on the valve. Under better conditions the oscillator tends to supply a bigger voltage but it is limited by the neon tube, the only result being a slightly higher harmonic content.

CHAPTER XVIII

CARRIER TELEPHONY

Introduction. Long distance telephone circuits require very costly line plant and telephone engineers are constantly seeking for ways of reducing the cost per circuit. It seems unlikely that any great reduction can be obtained in the cost of manufacture and laying of high grade cables. Aerial lines, whilst they are cheaper than underground cables, are nevertheless expensive; they involve heavy maintenance charges, are liable to serious interruption due to storm damage, and the number of wires which can be accommodated on a route is limited. Attention therefore turns to the better utilization of cable by the more efficient employment of cable pairs.

By using the first phantom superposed circuits as described in Chapter XV, a 50 per cent increase in the carrying capacity of a cable is obtained. This extra capacity is not obtained, however, without considerable expense, due to the better electrical balance required. Further superposing becomes uneconomic for the same reason; at any rate so far as land cables are concerned.

Carrier working aims at a better utilization of the frequency band which a line is capable of transmitting. For example, lightly loaded conductors are capable of transmitting a frequency band of 6 000 or 7 000 cycles, which is twice the band width necessary for a commercial telephone channel. It should therefore be possible to form two circuits on such a line provided that it is possible to shift the speech frequencies of one circuit by about 3 000 per sec. at the transmitting end of the line, and to restore them to their original position in the frequency spectrum at the receiving end of the line. The transmission channel obtained by this frequency shifting process is termed the *carrier channel*, the normal speech frequencies providing the *audio* channel. The separation of the channels is accomplished by means of filters.

This frequency shifting is possible in various ways and is known as *modulation*. The reverse process of restoring the frequencies is known as *demodulation*.

With unloaded cables or aerial lines there is no actual cut-off phenomenon, and it is therefore possible to arrange a large number of carrier channels on one line. This will be referred to later.

Modulation. A Frequency-shifting Process. The best known form of carrier working is wireless telephony, in which a carrier wave of very high frequency is varied in amplitude, or modulated, according to the speech frequencies which are being transmitted.

This process of modulation involves fundamental changes in

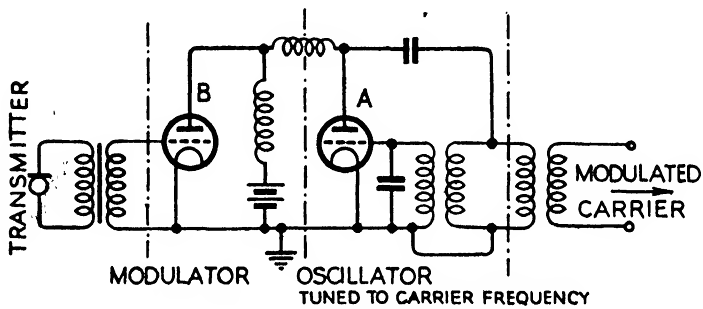


FIG. 357. ANODE MODULATION

the character of the carrier wave which make it, in effect, the frequency-shifting process referred to above.

A simple form of modulating circuit is shown in Fig. 357. The oscillating valve circuit *A* generates a carrier frequency and its amplitude is, within certain limits, proportional to the anode potential on the valve. By means of the modulating valve *B* the anode potential of *A*, and with it the amplitude of the carrier wave, is varied at the frequencies of speech from the transmitter. The effect is shown diagrammatically in Fig. 358. The way in which the character of the carrier wave is altered by the changes in amplitude is shown mathematically as follows. Let $V \sin ct$ be the carrier wave, let s be the speech frequency, and k be the fractional variation of the envelope, termed the *depth of modulation*, and usually expressed as a percentage. In Fig. 358 $k = 0{\cdot}5$. The envelope varies between $V(1 + k)$ and $V(1 - k)$. The complete wave is expressed by

$$V(1 + k \sin st) \sin ct \qquad . \qquad . \qquad . \quad (104)$$

By trigonometrical identities this can be written

$$V \sin ct + Vk \sin ct \sin st$$
$$= V \sin ct - V.\tfrac{1}{2}k . \cos (c + s)t + V. \tfrac{1}{2}k . \cos (c - s)t \quad (105)$$

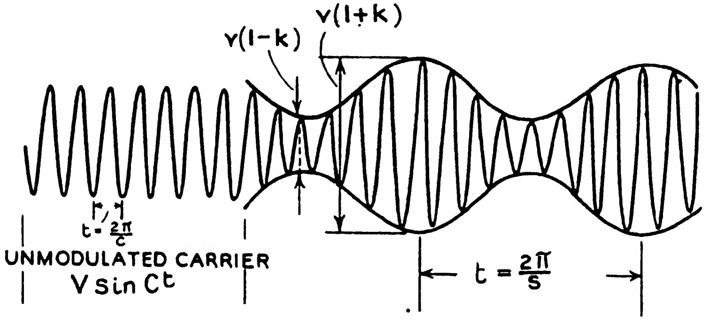


FIG. 358. MODULATED WAVE.

Thus modulation has turned the wave into a mixture of three frequencies, a plain carrier c, an upper side band $(c + s)$ and a lower side band $(c - s)$.

Fig. 359 shows a modulated wave and its three components. The wave is shown fully modulated, i.e. $k = 1$.

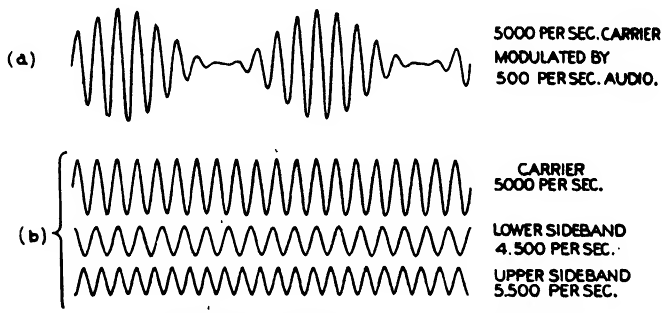


FIG. 359. WAVE MODULATED 100 PER-CENT
(a) Wave. (b) Equivalent components.

When a speech wave is used to modulate the carrier the band width of the complete modulated wave is twice the highest audio frequency used. (See Fig. 360.) All the frequencies of the original audio band are contained in and can be reproduced from either side band, and therefore one side band is all that need be transmitted; even the carrier frequency need not be transmitted provided a fresh carrier of exactly the same frequency

can be introduced at the receiving end of the channel. By suppressing one side band and the carrier frequency a band

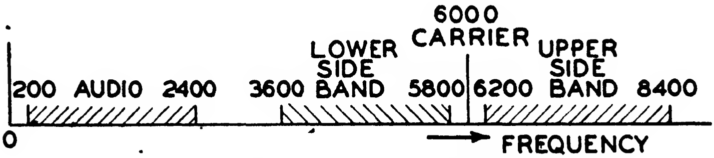


FIG. 360. CARRIER SYSTEM—FREQUENCY BAND

width equal to the original audio band width is sufficient. Furthermore there is a considerable saving in the power to be

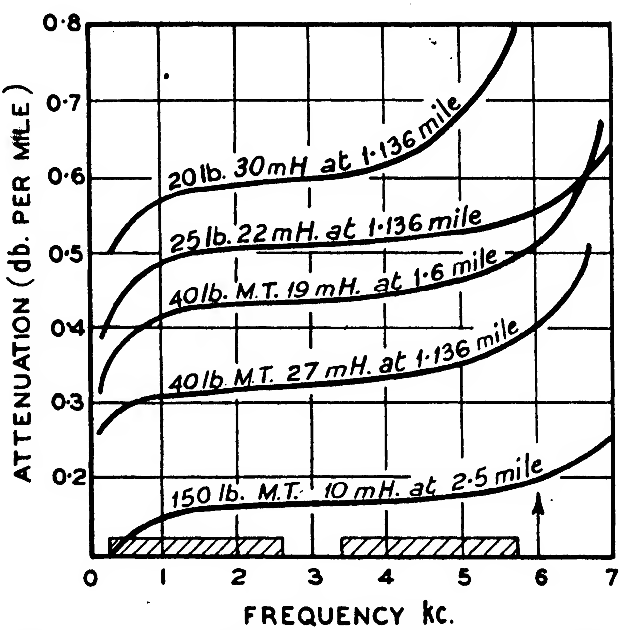


FIG. 361. ALLOCATION OF FREQUENCIES FOR TWO-CHANNEL WORKING

transmitted and that handled by intermediate amplifiers. Fig. 361 shows how the transmission band of a light loaded circuit can be allocated for two-channel working.

Modulation and Demodulation Circuits. In carrier telephone equipment it is convenient to use a single oscillator as a source of carrier current for the modulators and demodulators of one

or more carrier channels and therefore the anode method of modulation just described cannot be used.

Modulation is in reality a form of non-linear distortion and therefore circuits employing valves or metal rectifiers having non-linear characteristics can be used for modulation and demodulation, as will now be shown.

The valve characteristic has been given in Chapter XVII as

$$I_a = a(V_a + \mu V_g + e)^n$$

For the bottom bend of the curve n can be taken as 2; that is, the curve may be assumed to be a parabola. Also, for simplification regard V_a as a constant and $V_a + c = k$; then

$$I_a = a(k + \mu V_g)^2 \qquad . \quad . \quad . \quad . \ (106)$$

$$I_a + i_a = a(k + \mu V_g + \mu v_g)^2$$

from which

$$i_a = 2a\mu(k + \mu V_g)v_g + a\mu^2 v_g^2$$

or

$$i_a = a_1 v_g + a^2 v_g^2 \qquad . \quad . \quad . \quad . \ (107)$$

where a_1 and a_2 are constants.

This formula can also be used to explain the action of a copper dry plate rectifier.

Harmonic Distortion. If a single frequency signal $V \sin \omega t$ is applied to an amplifier with the characteristic of equation (107) the amplified signal will be

$$\left.\begin{aligned} i_a &= a_1 V \sin \omega t + a_2 V^2 \sin^2 \omega t \\ &= a_1 V \sin \omega t + \tfrac{1}{2}a_2 V^2 - \tfrac{1}{2}a_2 V^2 \cos 2\,\omega t \\ &\quad\ \downarrow \qquad\qquad\qquad \downarrow \qquad\qquad\qquad \downarrow \\ &= \text{Fundamental} + \substack{\text{Current}\\ \text{Direct}} + \text{Second harmonic} \end{aligned}\right\} \quad . \ (108)$$

Thus in addition to the amplified signal frequency, rectified current (d.c.) and second harmonic are obtained. This result has been obtained by regarding V_a as constant; actually there is a variation $V_a = - i_a R$ where R is the anode load resistance. It can be shown that if this is taken into account all harmonics to infinity are introduced, although only the second and possibly the third are important.

It was stated in Chapter XVII that a push-pull or balanced amplifier circuit eliminates the second harmonic if the valve characteristics are identical. This can be shown as follows. Referring to the schematic diagram, Fig. 362—

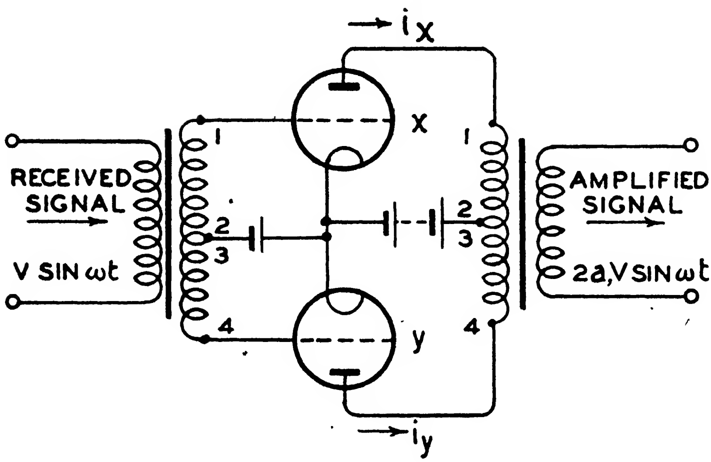


FIG. 362. PUSH-PULL CIRCUIT

The signals applied to the grids of valves x and y are in opposite phase; therefore

$$i_x = a_1 V \sin \omega t + a_2 V^2 \sin^2 \omega t$$
$$= a_1 V \sin \omega t + \tfrac{1}{2} a_2 V^2 - \tfrac{1}{2} a_2 V^2 \cos 2\omega t$$

and
$$i_y = - a_1 V \sin \omega t + a_2 V^2 \sin^2 \omega t$$
$$= - a_1 V \sin \omega t + \tfrac{1}{2} a_2 V^2 - \tfrac{1}{2} a_2 V^2 \cos 2\omega t$$

Remembering that the direct current components are not included in the output the amplified signal will be

$$i_x - i_y = 2a_1 V \sin \omega t \quad . \quad . \quad . \quad (109)$$

It is seen that the second harmonic has been eliminated.

It is interesting to note that if one of the transformer windings is reversed, say terminals 1 and 2, the amplified signal is $a_2 V^2 \cos 2\omega t$ giving square law amplification with doubling of the frequency. The same effect is produced by a double wave rectifier as shown in Fig. 363.

In this case the output signal (including d.c. components) is

$$i_x + i_y = 2a_2 V^2 \sin^2 \omega t \quad . \quad . \quad (110)$$

so that with an input signal v_g the output signal is $2a_2 v_g^2$.

Modulation. If two frequencies, audio ($A = V_1 \sin at$) and carrier ($C = V_2 \sin ct$) are applied to an amplifier or rectifier

circuit with the non-linear characteristics of equation (107) (see Fig. 364), then

$$v_g \doteq V_1 \sin at + V_2 \sin ct$$

$$\left.\begin{aligned} \text{and } i_a &= a_1 v_g + a_2 v_g^2 \\ &= a_1 V_1 \sin at + a_1 V_2 \sin ct + \tfrac{1}{2}a_2 (V_1 - V_2) \\ &\qquad - a_2 V_1 V_2 \cos (c - a)t + a_2 V_1 V_2 \cos (c + a)t \\ &\qquad - \tfrac{1}{2}a_2 V_1^2 \cos 2at - \tfrac{1}{2}a_2 V_2^2 \cos 2ct \end{aligned}\right\} \quad (111)$$

$$\begin{aligned} &= \text{audio} + \text{carrier} + \text{direct current} \\ &\quad + \text{lower side band} + \text{upper side band} \\ &\quad + \text{double audio} + \text{double carrier.} \end{aligned}$$

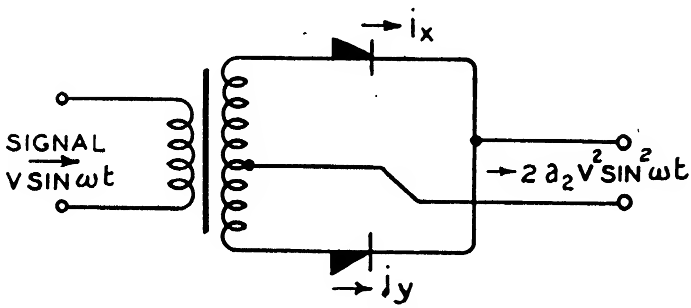


FIG. 363. DOUBLE WAVE RECTIFIER

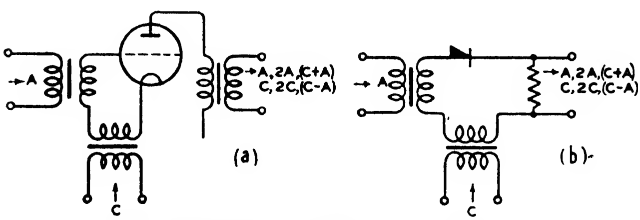


FIG. 364. RECTIFIER MODULATOR CIRCUITS

The rectifying action therefore causes six frequencies to be produced, A, C, $2A$, $2C$, $(C - A)$ and $(C + A)$, of which only the last two are suitable for carrier working.

By using a push-pull circuit or double wave rectifier as shown in Fig. 365, the carrier and double frequency components can be eliminated from the output. The required side-band can then be selected by means of filters, fairly easily. In practice

the balanced modulator suppresses the carrier by about 40 db. and a filter completes the process.

Demodulation. Any non-linear circuit such as those shown in Figs. 363, 364 and 365 can be used for the process of

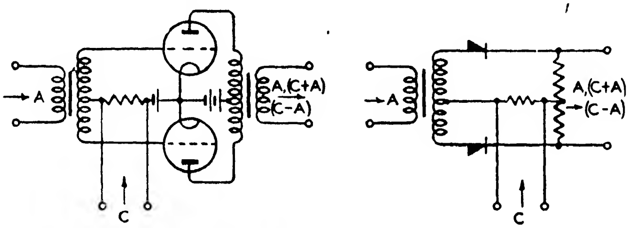


FIG. 365. BALANCED MODULATION

demodulation, i.e. the recovery of the original speech frequency band. It can be accomplished from one side-band and the carrier frequency only. If the carrier frequency is suppressed after modulation at the transmitting end of a carrier channel, for transmission reasons, it is necessary at the receiving end

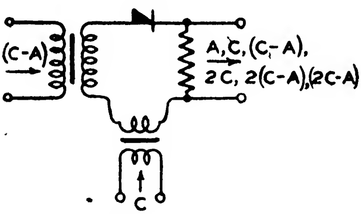


FIG. 366. DEMODULATOR

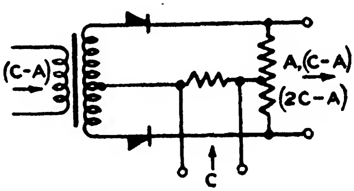


FIG. 367. BALANCED DEMODULATOR

of the channel to add a locally generated carrier of the same frequency as the original carrier to the received side-band before demodulation can be accomplished.

The local carrier can either be mixed with the received side-band or applied to the bridge of a balanced circuit as with a balanced modulator.

With the demodulator shown in Fig. 366—

If the rectifier has the characteristic

$$i_a = a_1 v_g + a_2 v_g^2$$

it is easily shown that the output contains A, C, $(C - A)$, $2C$, $2(C - A)$, $(2C - A)$. The first of these, the required audio frequency band, can be selected by means of a low pass filter.

With a balanced demodulator as shown in Fig. 367 it is found that the output contains three frequency components A, $(C - A)$, $(2C - A)$.

Carrier Schemes. The various ways in which carrier channels can be utilized to increase the circuit carrying capacity of cable circuits or aerial lines will now be considered. All the separate circuits required to construct carrier channels have now been dealt with in this and the preceding chapters, viz. filters, equalizers, hybrid-coils, amplifiers, oscillators, modulators and demodulators. Two principal factors governing the design of carrier circuits are, first, the frequency band width available above the ordinary audio channels, and second, whether the audio channels are worked four-wire or two-wire.

Two carrier systems used by the British Post Office will now be described. The first system is one designed to give an additional telephone circuit (GO and RETURN channels) on an aerial line without disturbing the ordinary audio working and direct current signalling, if used.

A schematic diagram of the terminal equipment for one end of the circuit is shown in Fig. 368. The carrier circuit is in effect a four-wire repeatered line, one channel using the upper side-band and one channel using the lower side-band. Referring to Fig. 368, the operation of the carrier is briefly as follows.

Speech currents are received in the hybrid transformer from the exchange equipment, they are passed to the amplifier combined with carrier frequency from the common oscillator and modulated; the products of modulation are first passed to the transmitting filter which suppresses the upper side-band and partially suppresses the carrier frequency; the output from this filter is then passed to line via the high pass filter. In the opposite direction of transmission, modulated upper side-band and carrier frequency are received from the line passed through the common high-pass filter, then through the band pass filter to the receiving amplifier and demodulator; from the demodulator speech frequencies are separated from the higher products of rectification and passed to the exchange side of the circuit via the hybrid transformer. At the other end of the carrier circuit the two band pass filters are of course reversed.

To prevent the carrier currents interfering with the working

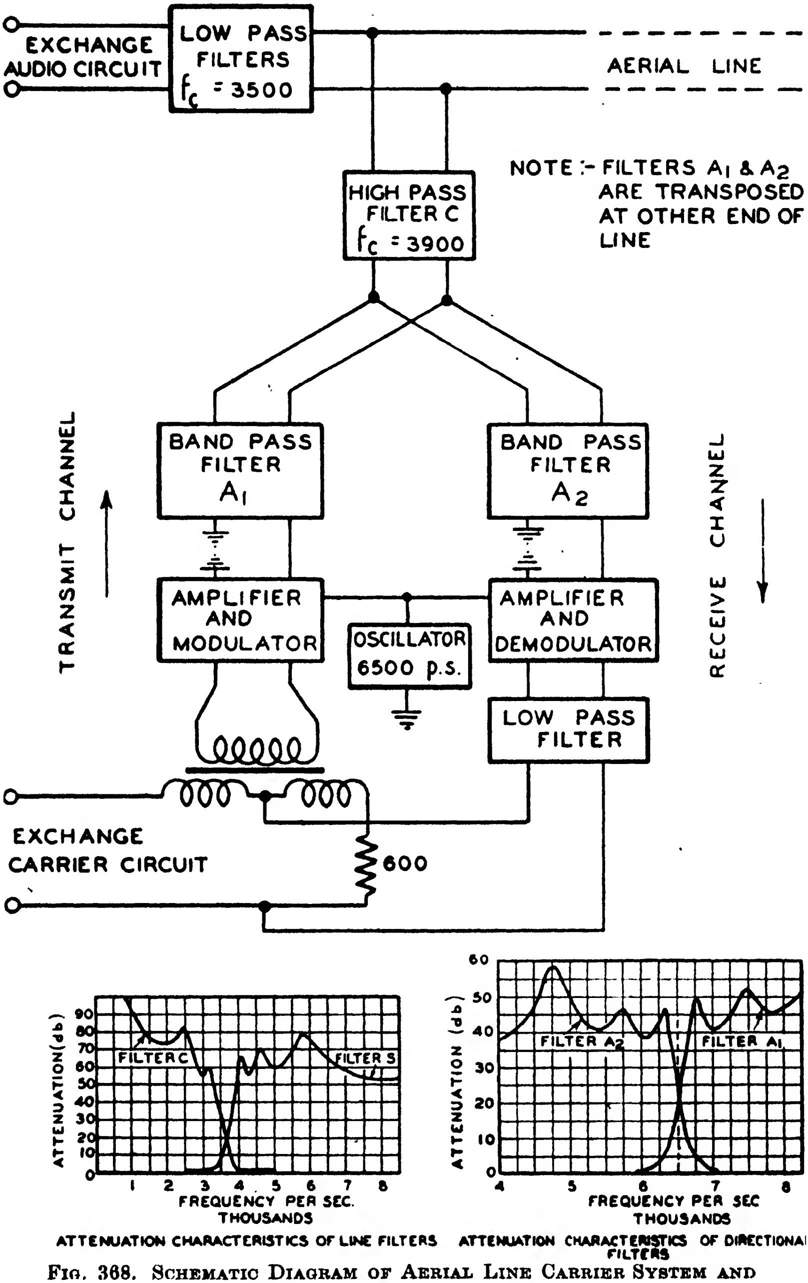


FIG. 368. SCHEMATIC DIAGRAM OF AERIAL LINE CARRIER SYSTEM AND FILTER ATTENUATION CHARACTERISTICS

of the normal physical circuit, low pass filters are interposed between the line and exchange, as shown in Fig. 368.

The circuits of the modulator, demodulator, and oscillator are shown in Fig. 369, and the filter circuits in Fig. 370. It is seen that the modulator consists of a dry-plate rectifier across the

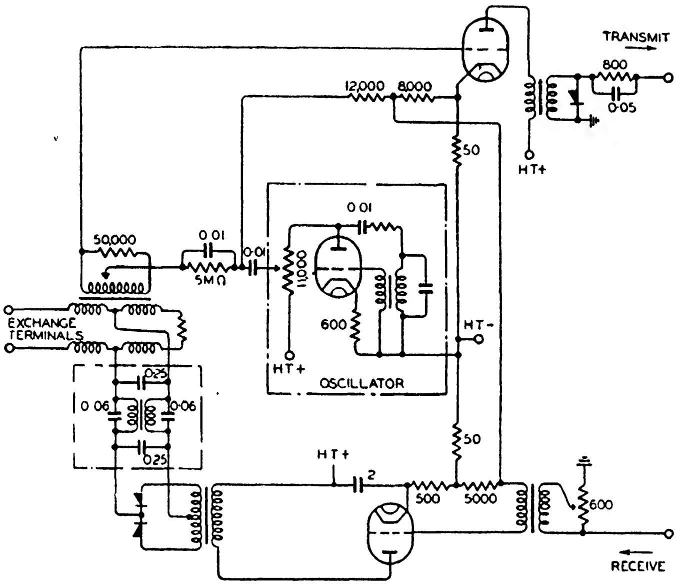


FIG. 369. MODULATOR AND DEMODULATOR CIRCUITS FOR AERIAL LINE CARRIER

output from the transmitting amplifier. Demodulation is effected by the double-wave dry-plate rectifier.

On the carrier circuit it is necessary to employ a voice-frequency method of signalling. A 500 cycle current, not interrupted, is used. This current is produced very simply as follows. When the exchange ringing key is operated a ring relay, not shown in Fig. 369, operates, and its contact adds or subtracts a small capacitance from the condenser in the tuned anode circuit of the oscillator. The carrier frequency is thereby shifted 500 per sec. to 6 000 or 7 000 per sec. depending upon whether the station considered transmits the lower or upper side-band. The carrier frequency at the other terminal station remains 6 500 per sec. and therefore the 6 000 or 7 000 per sec. current produces after modulation a 500 per sec. current which is used to operate a 500 per sec. signalling unit.

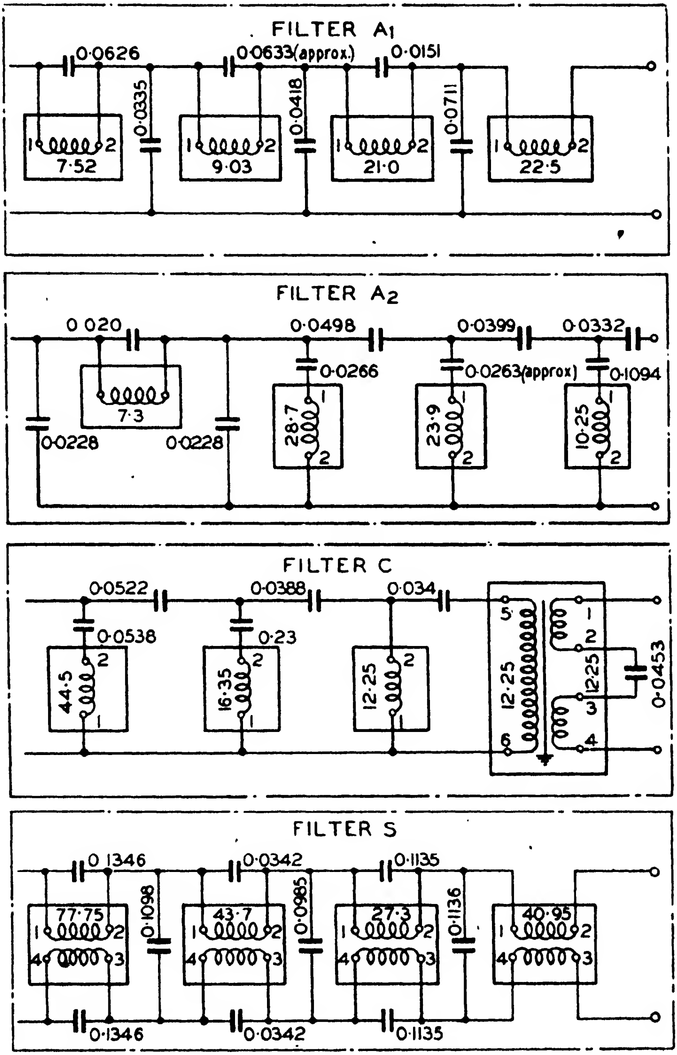


FIG. 370. FILTER CIRCUITS FOR AERIAL LINE CARRIER

The second system is a single-channel carrier system designed to double the circuit carrying capacity of cables used for four-wire repeatered circuits, and whose theoretical cut-off frequency is not less than 7 000 to 8 000 per sec. The intermediate repeaters amplify both audio and carrier circuit currents and no special equipment is necessary at intermediate

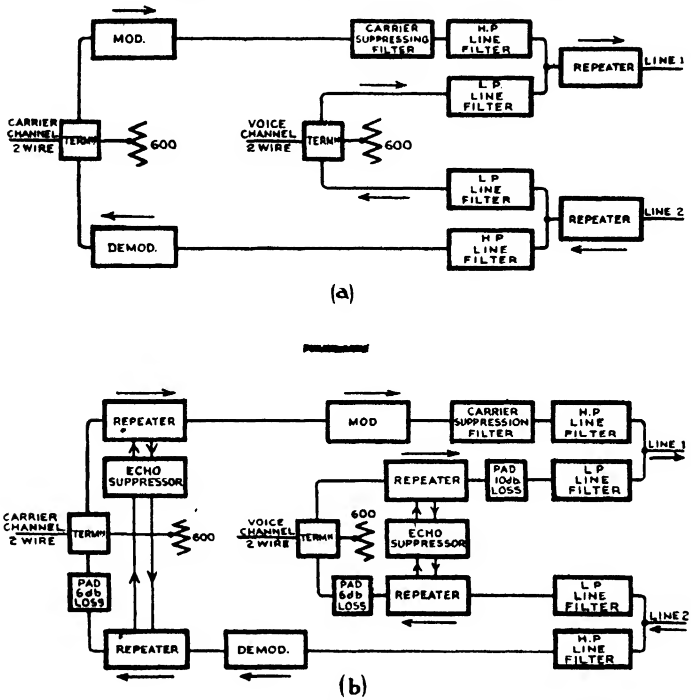


FIG. 371. CARRIER EQUIPMENT FOR UNDERGROUND CABLES
(*a*) Without echo suppressors. (*b*) With terminal echo suppressors.

repeater stations. A schematic diagram of the terminal equipment is shown in Fig. 371. The modulator and demodulators are of the type shown in Fig. 365, and are associated with the repeater.

Cross-talk between Carrier and Audio Channels. One of the most serious problems affecting the adoption of carrier circuits such as the four-wire system just described, is that of cross-talk between audio and carrier channel brought about by non-linear characteristics of the line and its associated repeaters. Non-linearity is introduced by loading coils and valves. Non-linearity

in the former is evident from the hysteresis curve of the iron core, and in the latter from the grid volts-anode current curve of the valve. It has been shown that with single frequencies non-linearity causes the production of harmonics, and the iron cores of the loading coils and transformers introduce principally third harmonic, whilst valves introduce principally second harmonic. Further, when two frequencies A and B are applied simultaneously, modulation products will be produced. With frequencies A and B the principal products in addition to the harmonics will be $(A - B)$ and $(A + B)$ from valves, $(2A - B)$ and $(2A + B)$ from iron cores.

Now considering the single-channel carrier system described above, using an effective band of 300 to 2 600 per sec. for the voice circuit and 3 400 to 5 700 per sec. for the carrier, it is evident that cross-talk will be produced in the carrier circuit by the following harmonics and modulation products of frequencies in the voice circuit—

(*a*) Second harmonics of frequencies 1 700 to 2 600 per sec.

(*b*) $(A + B)$ modulation products coming within the carrier band.

(*c*) Third harmonics of frequencies 1 130 to 1 900 per sec.

(*d*) $(2A + B)$ modulation products coming within the carrier band.

It is evident also that cross-talk may be produced in the voice circuit from carrier circuit currents by $(A - B)$ and $(2A - B)$ products.

There is a method of single-channel carrier working known as the *zweiband* system, used in Germany, which avoids any difficulty due to cross-talk between the carrier and audio channels. By this system a four-wire circuit is obtained from each cable pair by using audio working in one direction of transmission and a carrier channel for transmission in the opposite direction. The scheme has, however, the disadvantage that the two channels must be filtered out at each intermediate repeater station, although it is possible to make the amplifiers serve both directions of transmission.

The scheme has not been used in this country as it is uneconomical so long as inter-modulation cross-talk can be kept within reasonable limits by other means.

Voltage Limiters and Harmonic Compensators. Repeaters

are designed so that the valves operate on the straight portion of the characteristic curve as far as possible, but for carrier working further precautions are necessary to avoid non-linear distortion. First, it is essential that there shall be no flow of

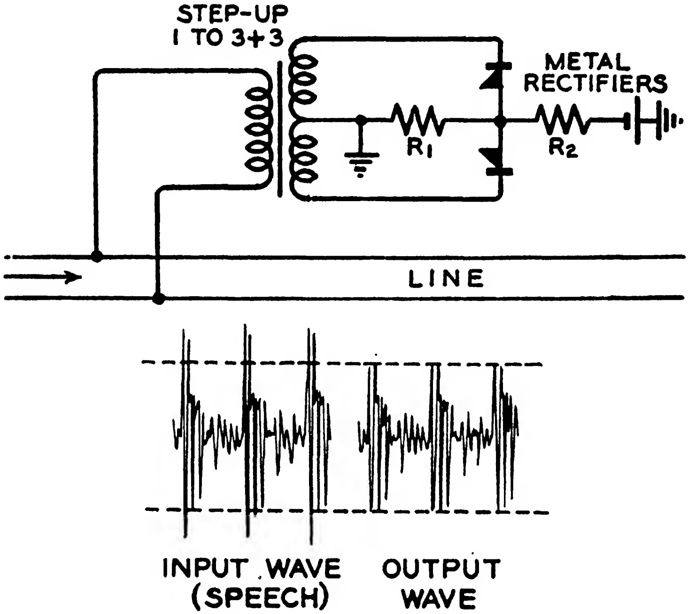


FIG. 372. VOLTAGE LIMITER AND ITS EFFECTS ON SPEECH CURRENTS

grid current with any signal strength which may be applied to the amplifiers. To ensure this for all operating conditions it has been found necessary to fit voltage limiters to both audio and carrier channels. A voltage limiting circuit employing dry-plate rectifiers, and its effect upon applied speech currents, is shown in Fig. 372. Second harmonic and second order modulation products can be greatly reduced by the use of push-pull repeaters, but the expense is not justified for single-channel carrier equipment. A simple method of reducing this distortion is by means of a harmonic compensator composed of a metal rectifier and shunting resistance introduced into the output circuit of the amplifier. (See Fig. 373.) The direction of the rectifier and the value of the shunting resistance are

arranged so that a distortion is introduced which is the opposite of that introduced by the valve.

Negative Feed-back Amplifiers. For multi-channel carrier systems a much greater freedom from the distortion which is introduced by ordinary repeaters is necessary, much greater even than can be obtained by the use of harmonic compensators

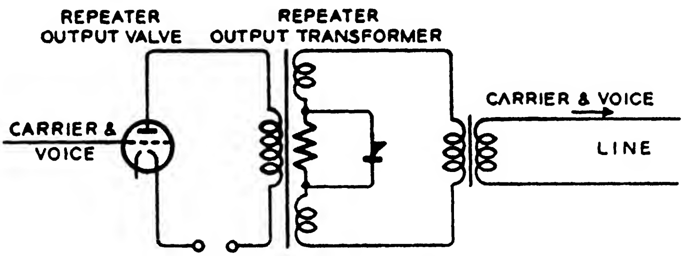


FIG. 373. HARMONIC COMPENSATOR

or by push-pull amplifying circuits. Further, the ordinary repeaters have several other disadvantages, when worked with the high gain required for such systems, the most important being the variation in the amplification caused by changes in

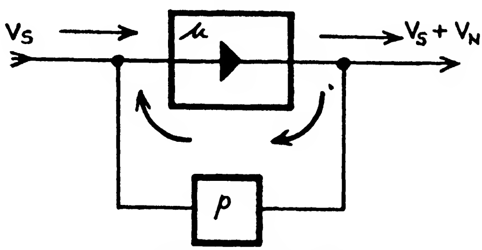


FIG. 374. SCHEMATIC OF FEEDBACK AMPLIFIER

the battery voltages and by changes in the valve characteristics. Another important consideration is the noise introduced by repeaters. This can be greatly reduced, but not entirely eliminated, by the use of valves with indirectly heated cathodes.

All these disadvantages are eliminated to a surprising degree by what is known as a *feed-back amplifier.* In this type of amplifier, it is possible to make the gain nearly independent of frequency and to make it independent of the changes in valve characteristics normally experienced. The amplifier is also unaffected by battery voltage changes within very wide limits.

Further, the phase distortion, harmonic distortion and the noise content are very greatly reduced.

The circuit consists essentially of an ordinary high gain amplifier in which part of the amplified voltage is led back through an attenuator to the input where it is applied out of phase with the original input signal. The following theory will help to explain the reason for the advantages of this circuit. The circuit is shown schematically in Fig. 374.

The following symbols are used.

v_s = Signal voltage applied

μ = Voltage ratio of amplifier without feed-back. 20 log μ = gain in decibels.

v_n = Noise voltage introduced by the amplifier without feed-back. This may also represent the harmonic distortion introduced.

β = Voltage ratio of feed-back circuit. Attenuation of path in decibels = 20 log β.

V_S = Output signal voltage with feed-back.

V_N = Output noise voltage with feed-back.

The total output voltage without feed-back is $\mu v_s + v_n$; with feed-back it becomes

$$(\mu v_s + v_n) + \mu\beta(V_S + V_N) = V_S + V_N$$

$$\therefore \; V_S + V_N = (\mu v_s + v_n)/(1 - \mu\beta)$$

$$= \mu v_s/(1 - \mu\beta) + v_n/(1 - \mu\beta) \quad . \quad (112)$$

If $\mu\beta$ is made large compared with 1 and of negative sign

$$V_S + V_N \doteqdot v_s/\beta + v_n/\mu\beta \quad . \quad . \quad (113)$$

Thus the output voltage becomes independent of the normal amplifier gain μ, and the noise and harmonic content is reduced to $v_n/\mu\beta$, but the gain has been very greatly reduced as the following numerical example shows.

Suppose μ = 1 000, i.e. the gain without feed-back is 60 db., and let $\beta = 1/30$, i.e. a 29·5 db. attenuation, then $V_S \doteqdot v_s \times 30$ = 29·5 db. This is a reduction of over 30 db., but it is now dependent upon the feed-back attenuation only. Further, the noise voltage and harmonic distortion normally generated becomes $v_n/33{\cdot}3$, i.e. reduced by 30·4 db.

The degree to which the gain is made independent of changes in the amplifier can be seen by the following numerical example.

Again taking $\mu = 1\,000$ and $\beta = 1/30$, the true gain from (112) is

$$\frac{1\,000}{1 + 1\,000/30} = 29{\cdot}13, \text{ i.e. } 29{\cdot}28 \text{ db.}$$

Now suppose μ is increased by 10 per cent, the gain becomes

$$\frac{1\,100}{1 + 1\,100/30} = 29{\cdot}2, \text{ i.e. } 29{\cdot}30 \text{ db.}$$

This theory does not indicate whether the circuit is stable or

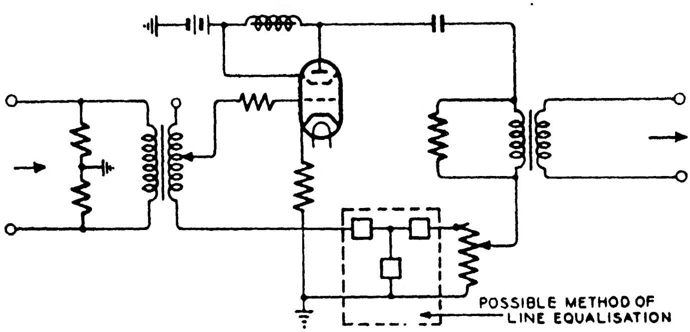


FIG. 375. CIRCUIT PRINCIPLES OF SINGLE STAGE FEED-BACK AMPLIFIER

unstable. For this purpose it is necessary to have a knowledge of the vector product $\mu\beta$ over the whole frequency range. Fig. 375 shows the circuit principles of a single-stage negative feed-back amplifier, employing a pentode valve. Since the output is approximately the same as the attenuation of the feed-back path, it is theoretically possible to obtain any desired attenuation equalization by including a suitable network in β. For line equalization β must have the same frequency characteristic as the line, not its inverse. There may, however, be serious objections to adopting this method from the point of view of repeater stability.

Multi-channel Carrier Systems. Multi-channel carrier systems working on unloaded cables specially designed for the purpose are now coming into use. Fig. 376 shows a schematic diagram of terminal equipment for a typical multi-channel system. For such systems a carrier channel spacing of 4 kc. will probably become standard practice.

Cables for Multi-channel Carrier Systems. The most important consideration in long distance telephony is noise interference and cross-talk, or more correctly the relative strength of signals and interference. Consider an ordinary repeatered circuit worked four-wire, the spacing of the line amplifiers and the gain introduced by each is governed purely by the possibility of cross-talk from other circuits in the cable; the level of

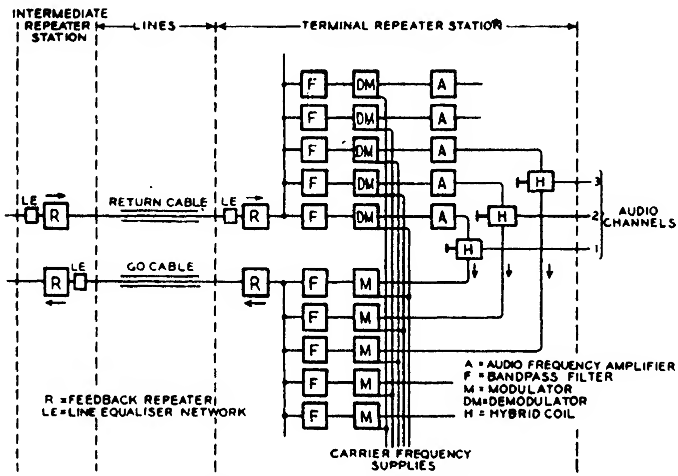


FIG. 376. SCHEMATIC ARRANGEMENT OF MULTI-CHANNEL CARRIER SYSTEM

the speech received at an amplifying station must not be so low that it is comparable with the noise and cross-talk voltage, and the level of the speech after amplification must not be so high that excessive interference to other circuits is produced.

Balancing of cable pairs was resorted to soon after loading came into general use, and with the general adoption of phantom circuits it became necessarily a very expensive business. For modern cables in which the phantom circuits are not utilized, simplified methods have been introduced. The relative positions of cable quads within each layer are changed from length to length of cable in a systematic manner, and at a limited number of joints crosses are inserted in the pairs so that the cross-talk within the quads is reduced to a minimum.

When four-wire working came into general use it became usual to allocate the pairs in certain layers of a cable for GO

channels and other layers for RETURN channels. This reduces the cross-talk between GO and RETURN channels which is, of course, aggravated by the difference in signal strength. For multi-channel carrier systems this idea is being carried to its logical conclusion by the provision of separate cables. When the possibility of cross-talk between GO and RETURN channels is eliminated by the use of separate cables the cross-talk which

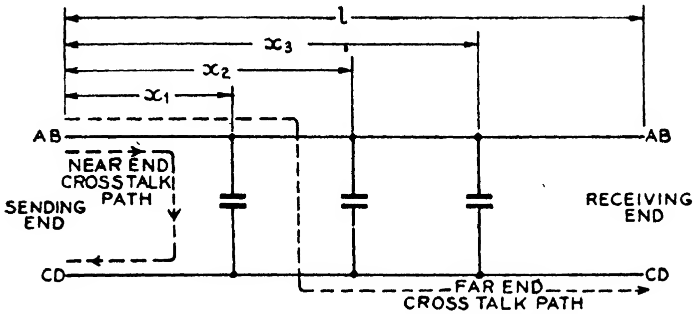


FIG. 377. SCHEMATIC DIAGRAM OF CROSS-TALK PATHS

remains between GO channels and between RETURN is a much simpler problem to deal with for the following reason.

Interference between cable pairs caused by unbalances in the electrical characteristics of the pairs produces cross-talk at both ends of the cable termed *near-end* and *far-end* cross-talk, relative to the direction of transmission on the pairs causing the interference. There is an important difference between near-end and far-end cross-talk. In Fig. 377 *AB* represents a pair which is causing interference with a pair *CD* due to unbalances existing at various points along the line (length l), say at points x_1, x_2 and x_3. The near-end cross-talk via x_1 has travelled a distance $2x$, that via x_2 has travelled $2x_2$, etc. Therefore the total near-end cross-talk is composed of components which, apart from the value of the unbalance, have been attenuated to different extents depending on the distances traversed and which have also undergone different phase changes. On the other hand the far-end cross-talk will be made up of components which have all suffered the same line attenuation, i.e. the attenuation length of the line, and which have all suffered the same phase change (provided that the near-end is correctly terminated so that reflection does not occur). In normal

four-wire working near-end cross-talk is the factor limiting repeater spacing.

If, however, GO and RETURN channels are in separate cables, only the far-end cross-talk need be considered which, because all its components are in phase, can be balanced out, or at any rate improved by about 20 db., by compensating capacitance unbalances connected at the receiving ends. Various ways of doing this have been devised, one of the most popular being to terminate the pairs of the "receive" cable on a framework which allows each pair to be connected to crosswires, arranged diagonally across the frame, and terminating both on the vertical and horizontal boundaries. Interconnection by small variable capacitances between any two unbalanced pairs is thus facilitated, and any subsequent rebalancing can be carried out without opening up the cables. The limiting factor in circuit design then becomes, not the cross-talk, but the repeater gain and noise level, which exceeds in importance the far-end cross-talk within the cables, and the near-end cross-talk between cables.

For cables designed to carry single-channel carrier systems it is possible to utilize very light loading provided that high grade loading coils are used, but when multi-channel systems are required it is essential to use unloaded cables. When more than two or three carrier channels are required on each pair, the use of separate cables for GO and RETURN channels must be considered. The number of cable pairs required will, of course, decrease as the number of carrier channels worked on each pair is increased, and a logical development of this is a pair of cables providing one transmission path in each direction on which a large number of carrier circuits can be worked. For such a system the terminal equipment will obviously be very expensive and could only be contemplated for long-distance circuits.

Recent developments, and in particular the negative feed-back amplifier, have made it possible to consider the use of 'wide-band' transmission systems accommodating as many as 200 carrier channels on one transmission path. For this purpose cable design has been approached from a different angle.

Coaxial Cables. What are known as *coaxial* cables have been found extremely suitable for wide-band transmission. Short

lengths of such cables have been in use for many years for high frequency transmission to feed radio transmitting aerials.

One of the main advantages is that at high frequencies the coaxial cable becomes self-screening. Fig. 378 shows one form of coaxial cable. The outer conductor is a copper tube, or copper tape wound to this form, while the inner conductor is a copper wire positioned at the centre of the tube by spacing pieces of insulating material of low dielectric loss. Other forms of coaxial cable have been designed and laid, the differences being mainly in the manner of supporting the central conductor. A coaxial cable with solid dielectric is described in Chapter XIX.

When the cable is carrying direct current or low frequency alternating current the intensity of the magnetic field at a

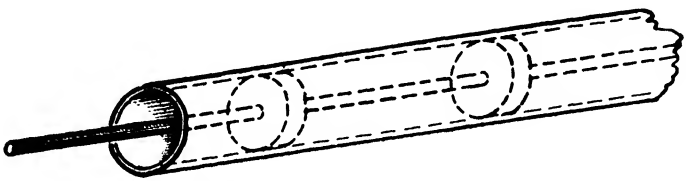


FIG. 378. SCHEMATIC DIAGRAM OF A CO-AXIAL CABLE

point r cm. from a straight wire carrying a current I is $2I/r$ c.g.s. units. From this it is easily proved that if the central conductor of the cable is located exactly at the centre of the outer tube then there will be no external magnetic field.

At very high frequencies a skin-effect causes the current to concentrate near the surface of the conductors, i.e. near the surface of the central conductor and the inner surface of the surrounding tube. In fact, the energy is transmitted as an electromagnetic wave in the space between the conductors and the velocity will approach that of light. As the wave is propagated in one dimension only, attenuation will be due purely to absorption and dissipation near the surface of the conductors. With a good conductor like copper the depth of penetration will be only a fraction of a millimetre at frequencies of, say, several 100 kc., and the thickness of outer conductor required for mechanical reasons will be sufficient to ensure that the attenuation is independent of the thickness of the outer conductor, and that the latter will give effective shielding from external interference, and there will be no external magnetic field even

if the inner conductor is not located exactly at the centre of the outer tube.

With this condition the attenuation depends on the relative dimensions of the conductors. For maximum efficiency the outer diameter of the central conductor should be 1/3·6 times the inner diameter of the outer tube. The theoretical attenuation of a $\frac{1}{2}$-in. coaxial cable (outer conductor $\frac{1}{2}$-in. internal diameter) with air as the dielectric, is 3·0 db. per mile at 10^6 cycles per sec. and will be proportional to the square root of the frequency. In practice this will be increased by the spacing pieces supporting the central conductor.

London-Birmingham System. The London–Birmingham coaxial cable forms part of a system which is being extended to Manchester and Newcastle, and contains four coaxial cores, two being used for telephony (GO and RETURN cores) and two for television. Each repeater section is from 6 to 7·5 miles in length, and the attenuation over a length of 7·5 miles varies from 20 db. at 500 kc.p.s. (0·5 megacycle per sec.) to 50 db. at 2 100 kc.p.s. (2·1 megacycles per second). The frequency band used has a width therefore of 1·6 megacycles per second, and this was determined from television considerations. The four-stage amplifiers and equalizers used at the intermediate and terminal repeater stations have overall frequency characteristics, which result in the output signals being reasonably uniform in level over the entire frequency band. Due to the cable characteristics, of course, the signal levels at the receiving end of each section will be very different at the various frequencies, but the subsequent equalization and amplification corrects this before transmission into the following section. The initial carrier frequency spacing employed is 5 kc.p.s., but this may subsequently be reduced to the more standard 4 kc.p.s. The corresponding number of channels obtainable is 320 and 400 respectively.

The first 8 audio channels are modulated by carrier frequencies from 65 to 100 kc.p.s., and, as the lower sidebands only are selected by filters, the 8-channel "Group" occupies a band width of 40 kc.p.s. (60–100 kc.p.s.). Each "Group" of 8 audio circuits is treated in the same way, and the first "Group" is modulated further by a carrier of 400 kc.p.s. As the band width of the group is 40 kc.p.s. (60–100 kc.p.s.) the side-bands

produced by this process are 300–340 kc.p.s. and 460–500 kc.p.s. Again, filters are employed to select the lower sideband, and the 2nd, 3rd, 4th, and 5th groups are similarly treated, with carrier frequencies of 440, 480, 520, and 560 kc.p.s., thus producing a "super-group" of 200 kc.p.s. band width in the frequency range 300–500 kc.p.s. Now, with 320 channels there will be 40 "groups," and 8 "super-groups."

The 8 "super-groups" have each a band width of 200 kc.p.s., and "super-group" No. 1 is now modulated by a carrier of 1 000 kc.p.s., "super group" No. 2 with 1 200 kc.p.s., and so on up to "super group" No. 8, with 2 400 kc.p.s. resulting, after selection of the lower sidebands, in a frequency band of width 1 600 kc.p.s., between the limits 500 and 2 100 kc.p.s. The 320 channels are then evenly spaced over this band, and although each channel has undergone three modulation processes, only 21 different carrier frequencies have been employed, as against the 320 which would be necessary were individual channel modulation to the required ultimate frequency employed. Great simplification of carrier control is thereby obtained, as well as more uniformity in filter design. The filters used in this system employ quartz crystal resonators in place of tuned LC circuits, but the treatment of crystal technique is beyond the scope of this book. Similar demodulation processes are employed at the receiving end, and a master oscillator and pilot carrier of 400 kc.p.s. are utilized to lock the modulating and demodulating carrier frequencies at the terminal stations. Apart from the filter design and the employment of group modulation, the various processes follow the standard carrier system practice, and should be easily understood from the foregoing descriptions. A novel feature is the employment of the concentric pairs to supply a.c. at 350 volts 50 c.p.s. for the operation of the intermediate repeater station power plant, a selected supply station transmitting power to one repeater station in each direction of the line, thereby greatly minimizing the risks of breakdown due to power failure. The four cores are connected in parallel, via low pass filters, for this purpose, and no interference with the communication system is experienced.

12-Channel Systems. Where a very large number of circuits is required between two terminal points, the coaxial system

described above is an economic solution, though the terminal equipment is expensive. For smaller installations, a 12-channel

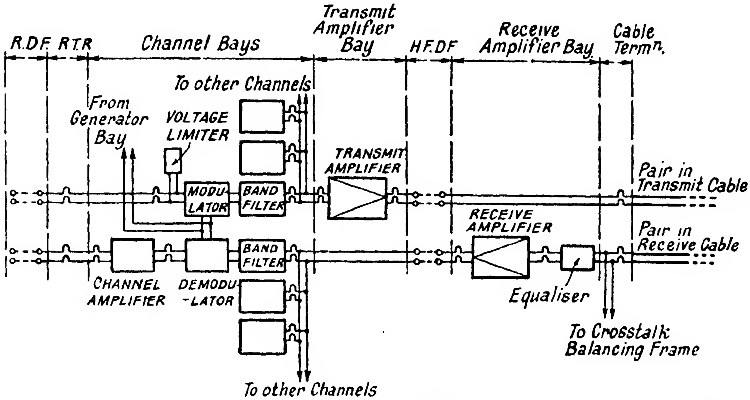


FIG. 379. SCHEMATIC ARRANGEMENT OF EARLIEST 12-CHANNEL TERMINAL EQUIPMENT

system has been adopted, utilizing 40 lb. conductors in star-quad formation, with separate GO and RETURN cables, each of

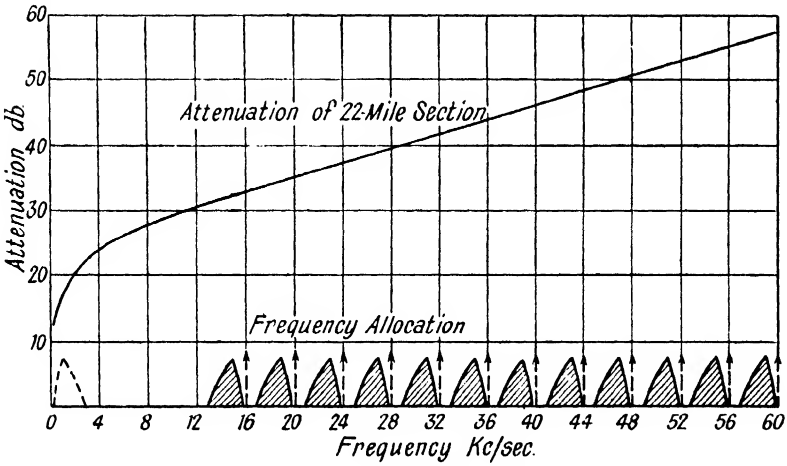


FIG. 380. FREQUENCY ALLOCATIONS IN ORIGINAL 12-CHANNEL SCHEMES

24 pairs. The maximum number of channels obtainable on this basis is $12 \times 24 = 288$.

The spacing of the repeater stations is determined by the crosstalk limitations, attenuation of cable, and gain-frequency characteristics of the amplifiers.

Original Twelve-channel Schemes. With the type of cable employed, the attenuation varies from 1·1 db. per mile at 4 kc.p.s. to 2·6 db. per mile at 60 kc.p.s. A maximum gain of 60 db. per repeater, with a suitable frequency characteristic, can be obtained, and the repeater stations are spaced at 22 mile intervals to give the desired result. The channel spacing is the standard 4 kc.p.s., and the 12 channels occupy the 16–60 kc.p.s. band, the lower sidebands only of the individual circuits being transmitted. There is a band, therefore, from 0 to 12 kc.p.s. which is not employed, owing to the difficulty in designing an amplifier which would satisfactorily cover the whole range. At the terminal stations, each audio channel is modulated and demodulated, either separately, as in Messrs. S. T. & C. company's system, or in two stages of group modulation, as in Messrs. G. E. Company's scheme. Channel filters with suitable characteristics are employed at the terminals, whilst at the intermediate stations one amplifier per channel in each direction of transmission is required. The crosstalk balancing networks are installed at the receiving end of each repeater section, and as the various channel carrier frequencies and spacings are standard, interconnection of channels between routes will be practicable. The schematic arrangement and frequency band allocations are shown in Figs. 379 and 380.

Later Developments. The earlier schemes for 12-channel working were satisfactory in performance, but were not standardized, and at the 1938 C.C.I.F. conference at Oslo the recommendations regarding the characteristics of an international 12-channel system were laid down. These differed in certain important respects from the current British systems, and in the future installations the international specification will be followed. The two major differences are in respect of the sidebands transmitted to line—the earlier systems used the lower sidebands, and had an effective band-spread of 0·3 to 2·6 kc.p.s. per channel, while the later systems will employ upper sidebands, with a band spread of 0·3 to 3·4 kc.p.s.

The use of an upper rather than a lower sideband does not affect the operation of the system in any way, except that, with the same carrier spacing of 4 kc.p.s. and the same overall band width transmitted to line, the lowest carrier frequency is 12 kc.p.s. instead of 16 kc.p.s.

The extension of the channel band-width necessitates the use of a different filter and modulation technique, as the normal reactor type of filter with single frequency changing would not give adequate suppression. In the new system, therefore, quartz crystal filters are employed, and as these filters are most efficient at frequencies above 60 kc.p.s., the 12-channel group is formed by modulating the audio channels to form a group of circuits in the frequency range 60 to 108 kc.p.s., the carrier frequencies being steps of 4 kc.p.s., between the limits of 64 and 108 kc.p.s., the lower sidebands being selected.

To render this frequency range suitable for transmission over the cable circuit, it is further "group-modulated" by a carrier frequency of 120 kc.p.s., which results in the formation of a band of frequencies lying between 12 and 60 kc.p.s., and comprising the twelve channels, with carrier frequencies ranging from 12 to 56 kc.p.s. in 4 kc.p.s. steps, and the upper sideband for each channel, owing to the "inversion" which occurs in the frequency spectrum for these products of group modulation. This is the desired result, and whilst the overall band width and carrier spacing are the same as in the earlier systems, the choice of the upper sideband for transmission will result in the practicability of extending such carrier systems to the Continent without demodulation and separation of the various channels. The only change required from the earlier layout (Fig. 379) is the introduction of the group frequency changing equipment between the channel filters and the line amplifiers on the transmitting side of the installation.

The increase in the frequency band width transmitted per channel results in superior quality transmission, which is desirable particularly for international circuits, and this is accomplished by suitable modification of the characteristics of the channel amplifiers and the change in filter and modulation practice mentioned above.

As the earlier installations had demonstrated the feasibility of transmitting frequencies well in excess of the 60 kc.p.s. limit, advantage has been taken in the revised design to cater for an ultimate extension of the frequency range to 108 kc.p.s. This will enable group-modulation to be dispensed with for half of the circuits, and as the range of 60–108 kc.p.s. has also

been recommended by the C.C.I.F. as a basic group for coaxial systems (4 kc.p.s carrier spacing and lower sidebands), extension of the upper 12 channels to a coaxial system is practicable if subsequently desired. The cable attenuation at the highest frequency (108 kc.p.s.) is too great to allow the use of the former 22-mile spacing of repeater stations with repeater gains of 65 db. maximum, and the new system will have repeater spacing of 16 miles, and amplifiers capable of dealing with the ultimate range of frequencies likely to be employed.

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CHAPTER XIX

SUBMARINE TELEPHONE CABLES

THE early submarine telephone cables were similar to telegraph cables, that is to say, they had heavy copper conductors insulated with a solid gutta percha (g.p.) dielectric and were mechanically protected with galvanized iron armouring laid over fillings of tarred hemp and similar materials.

Solid core cables are all of very similar construction. Fig. 381 shows a full size section of such a cable. It has four conductors each made up of seven strands of 20 lb. per mile copper wire

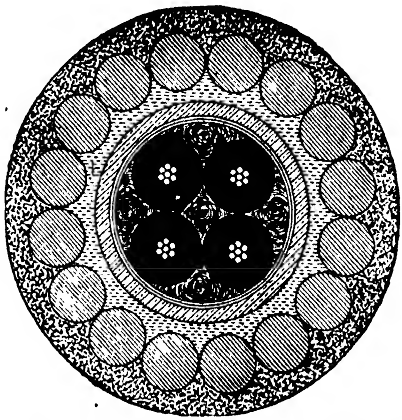

FIG. 381. SECTION OF ANGLO-BELGIAN CABLE
(Full size.)

(total 160 lb. per naut). Each conductor is coated with gutta percha and formed round a core and made cylindrical with tarred hemp. Over this is a layer of ozokerited cotton tape, then a layer of hemp. Over this is wound an armour of sixteen galvanized iron wires 0·28 in. diameter and coated with tar. The whole is covered with two windings of tarred hemp. Table 7 gives a schedule of important submarine telephone cables with solid dielectric and their electrical constants.

Gutta percha, which was used in the earliest submarine cables, is the sap obtained from certain species of trees in the Malay archipelago. Balata, which has been used subsequently,

is obtained from trees of the same species in South America. It is more uniform than gutta percha. Both gutta percha and balata contain about 40 per cent of resin and impurities which for electrical reasons it would be desirable to eliminate, but for mechanical reasons they are most suitable in the commercial state. Balata softens with heat and can be applied in a uniform layer to the wire to which it adheres. It hardens on cooling and stands up to much handling.

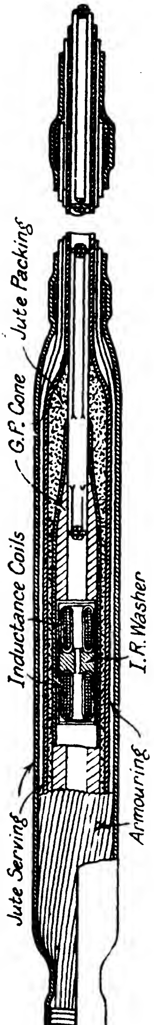

FIG. 382. SUBMARINE LOADING COILS

The use of balata in place of gutta percha has enabled the value of G/C to be reduced from about 110 to about 12, with a consequent improvement in transmission constants. The electrical constants of balata are approximately—

Conductivity: 66×10^{-12} mho/cm.^{3}
Dielectric constant at 2 000 cyc: 3.1.

A number of coil-loaded submarine cables has been used; five such cables which are still in use are shown in Table 7.

The method of inserting a loading coil in a submarine cable is shown in Fig. 382. This shows the two side-circuit loading coils. A coil for the phantom is added when required just beyond the other two, and only increases the length of the "bulge" by about 8 in. The loading coil cores are, as shown, arranged with their axes in the length of the cable, and the coils themselves are separated with a rubber washer. The extra diameter at the coils is toned down by means of a gutta percha cone at each end, and further protected by jute packing, as shown. The overall diameter of the "bulge," 4½ in., is about twice that of the cable, and armouring is obtained by doubling the number of armouring wires over the "bulge," and for a short distance beyond. On the "bulge," therefore, the extra armouring

wires just fill in the spaces which would otherwise have been left.

The great disadvantage of coil loading for submarine cables is that when repairs have to be made accurate spacing of the coil cannot be maintained.

Continuous loading, which consists of lapping the copper conductors with a soft iron wire of from 5 to 20 mils in diameter, was used before coil loading; the first submarine cable loaded in this way was laid in 1902 between Elsinore and Helsingborg. The amount of inductance which was added in this way was small, and to some extent its benefit was annulled by the additional capacitance also added. Later continuously loaded cables have had loading wires of higher permeability alloys.

All the cables laid since 1923 between this country and the Continent have been lead-covered paper-core cables. These cables and their electric constants are shown in Table 8. As the wires in paper-core cables are in effect air-spaced, a considerable reduction in attenuation constant is obtained, but this air-spacing also prevents such cables being used in deep water where the great pressure would flatten the cable. For this reason the Port Erin–Donaghadee cable has a solid dielectric whilst the Blackpool–Port Erin cable is a paper-core cable.

Fig. 383 shows the cross-section of a seven-quad paper-core sea cable of the type used for the first two cables shown in Table 8.

In the design of sea cables several points have to be considered which do not arise in the case of land cables. First is the difficulty of handling heavy cables and of making joints at sea, and the time required to do so prohibits the use of cable with a large number of conductors. Second, cables are liable to be damaged at any time, particularly by ships' anchors, and when a breakdown occurs repairs cannot be effected quickly. In some cases the cable repair ship may have to grapple for several days or even weeks before the damaged cable can be hooked. Consequently it is even more important than in the case of land cables that alternative methods of routing calls should be available. On the other hand, the high cost of submarine cables makes it imperative that the fullest use should be made of the transmission channels, and expensive terminal equipment is justified to do so. With the development of

TABLE 7

Particulars of some Submarine Telephone Cables with Solid Dielectric

Cables	Date Laid	Length (nauts)	No. of Conductors	Weight (lb. per naut per conductor)	Loading	Constants per naut (at 800 cyc. approx.) R (ohms)	L (mH.)	C (μF.)	G/C	Z_o	β	Side or Phantom Circuits
Abbott's Cliff–Grisnez No. 2 (G.P.)	1897	21·6	4	160	Unloaded	21	2	0·156		148 $\overline{\rvert 25{\cdot}8}$	0·0546	S
								0·312		69·9 $\overline{\rvert 30{\cdot}4}$	0·0595	Ph
Abbott's Cliff–Grisnez No. 3 (G.P.)	1910	20	4	160	0·1 H. coils at 1 naut	20·9	102	0·138	120	858 $\overline{\rvert 0{\cdot}9}$	0·0166	S
Abbott's Cliff–Grisnez No. 4 (G.P.)	1912	22·4	4	300	1 layer 8 mils	8·54	12·4	0·176	109	278 $\overline{\rvert 2{\cdot}3}$	0·0171	S
Nevin–Howth (Balata)	1913	63·4	4	160	0·1 H. coil at 1 naut	21·0	102	0·166	12	690 $\overline{\rvert 2{\cdot}7}$	0·015	S
						10·3	51	0·320	12	446 $\overline{\rvert 0{\cdot}9}$	0·015	Ph
Dungeness–Audresselles No. 2 (Balata)	1918	27·6	4	160	0·1 H. coils at 1 naut	20·5	100	0·166	20	778 $\overline{\rvert 5{\cdot}6}$	0·0145	S
						10·3	50	0·320	20	380 $\overline{\rvert 0{\cdot}4}$	0·014	Ph
Dungeness–Audresselles No. 3 (Balata)	1918	26·6	4	Mixed 160, 310	0·1 H. coils at 1 naut						0·0120	S
											0·0117	Ph
Aldeburgh–Domburg No. 1 (Balata)	1922	83·2	4	160	0·1 H. coils at 1 naut		102	0·166		800 $\overline{\rvert 1{\cdot}0}$	0·145	S
							51	0·328		410 $\overline{\rvert 1{\cdot}0}$	0·137	Ph
Port Moira–Donaghadee (Balata)	1922	20·1	4	169	2 layers 8 mils	17·4	24·7	0·183		370 $\overline{\rvert 3{\cdot}9}$	0·0237	S
						8·8	11·9	0·363		182 $\overline{\rvert 3{\cdot}9}$	0·0233	Ph
Port Erin–Ballyhoman (2 cables: Balata)	1929	31·2	4	160 (7-strand tarred)	Unloaded	14·5		0·156		149 $\overline{\rvert 27{\cdot}9}$	0·056	S
						7·5		0·340		70·4 $\overline{\rvert 32{\cdot}5}$	0·059	Ph
Key West–Havana (Paragutta)	1921	104	1	350	1 layer 0·2 mm.	4·8	4·1	0·310		118 $\overline{\rvert 6}$	0·0216	S

TABLE 8

Particulars of some Submarine Cables with Paper-core and Lead Sheaths

Cable	Date Laid	Length (nauts)	No. of Conductors	Weight (lb. per naut per conductor)	Loading	Constants per naut (at 800 cyc. approx.)					β	Side or Phantom Circuits
						R (ohms)	L (mH.)	C (μF.)	G/C	Z_0		
Canterbury (Dumpton)–La Panne No. 1 (Anglo-Belgian)	1926	48·7	All 7-quad, 28 wires	117	1 layer 8 mils.	20·8	12·6	0·092	20	387 ∠7·8	0·0265	S
						10·3	5·93	0·262		157 ∠8·6	0·0322	Ph
Seabrook–Audresselles (Canterbury–Boulogne)	1927	50				19·52		0·0902		387 ∠8·6	0·0273	S
						9·76		0·272		157 ∠9·6	0·0329	Ph
Dumpton–La Panne No. 2 (Canterbury) (Anglo-Belgian No. 2)	1930	50·4								379 ∠9·5	0·0285	S
										150 ∠9·8	0·0347	Ph
Aldeburgh–Domburg No. 2	1923	82·4	16	165	2 layers 16 units	16·1	18·7	0·107	24·3	414 ∠6·5	0·020	S
						7·84	9·1	0·311		170 ∠6	0·0238	Ph
Aldeburgh–Domburg No. 3	1926	86·25	17*	138	1 layer 16 mils silicon iron	15·5	16·22	0·082	16	440 ∠5·35	0·018	S
						7·6	8·04	0·219		185 ∠5·5	0·021	Ph
Blackpool–Port Erin	1929	69·1	17*	118	1 layer 8 mils	20·4	12·2	0·090		370 ∠8·8	0·0287	S
						10·3	5·9	0·258		155 ∠9·4	0·0348	Ph
Seabrook–Le Portel (Canterbury–Boulogne)	1930	32·1	7-quad	92·5	1 layer 5·9 mils	24·66	18·28	0·0773		477 ∠7·7	0·0264	S
						11·85	8·64	0·2231	19	200 ∠7·5	0·0303	Ph
St. Margaret's–La Panne	1932	49·1	30-quad		Intermittent continuous loading in lengths of ⅛ mile (230 metres)	70·2	23·2	0·0734	16	610 ∠17·25	0·0588	S
St. Margaret's–Calais	1933	26·31	19-quad	57·5	Unloaded		1·1	0·1035		244 ∠38	0·0794	S
							0·36	0·2544		unknown	0·090	Ph

multi-channel carrier technique, the need for submarine cables with large numbers of conductors will no longer exist. Concentric cables which have already been referred to will be used,

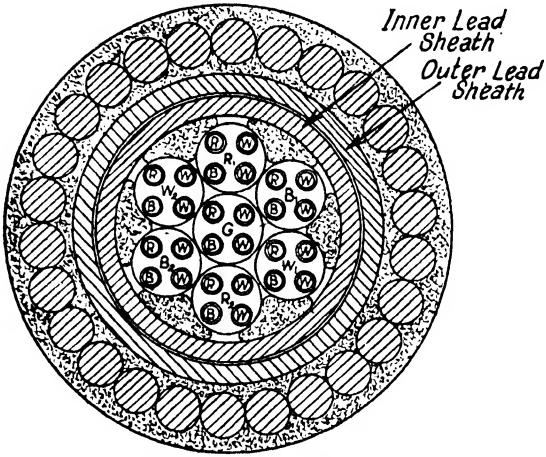

FIG. 383. CROSS-SECTION OF PAPER-CORE SEA CABLE

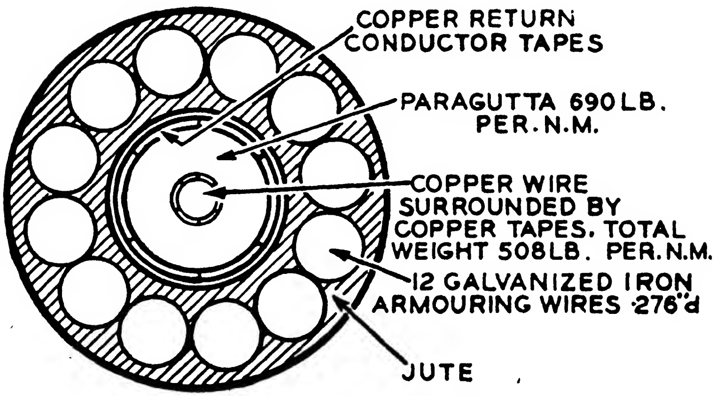

FIG. 384. CROSS-SECTION OF CO-AXIAL SEA CABLE

and from what has been said it will be obvious that such cables have great advantages as submarine links. The British Post Office has recently laid two such cables between this country and Holland. Fig. 384 shows a cross-section of the type of cable. Similar cables are used between Australia and Tasmania.

On account of the great pressure which submarine cables must stand, a solid dielectric will be necessary between the inner and outer conductors. For this purpose, paragutta will be used, which will enable the dielectric losses to be kept small, even at very high frequencies. Paragutta is a mixture of deproteinized rubber, and gutta percha freed from resin and other impurities. Special mineral wax is added for mechanical reasons and to reduce the cost. Both the conductivity and permittivity are less than for gutta percha or balata, but the actual values depend largely on the proportion of the constituents. The last cable shown in Table 7, Key West to Havana, was the first cable with paragutta as dielectric. It is 108 nauts in length and provides three carrier circuits.

CHAPTER XX

TRANSMISSION STANDARDS AND ALLOWANCES

General Considerations. One of the telephone engineer's principal aims is to make possible, at reasonable cost, telephone communication between any two subscribers with a quality of transmission not greatly inferior to that obtained between two telephones connected to the same telephone exchange. In recent years the development of international telephone circuits and radio telephone channels has proceeded rapidly, and it is now possible for subscribers in this country to obtain connection with about 95 per cent of the telephone subscribers of the world.

That the quality of reproduced speech obtained on local telephone connections should have been regarded in the past as a standard has perhaps simplified the problem of long distance telephony, especially in its early stages, both from the technical and economic aspects. This standard is determined very largely by the electro-acoustic properties of the transmitters and receivers used which, for the ordinary commercial instruments, could only be described as poor. It enabled, for instance, very heavy loading to be used on trunk cable circuits so reducing the cut-off frequency, sometimes as low as 2 000 per sec. After the first rapid development of long-distance telephone circuits, new uses, arose for those lines which demanded better quality transmission such as picture transmissions, music transmissions, and high quality speech transmission; but probably just as important in this respect have been the improvements in the electro-acoustic properties of the telephone instruments themselves. The Post Office telephone set No. 162, for instance, with its transmitter inset No. 10, is much superior in its frequency-response characteristics to the old solid-back transmitter. These improvements in instruments and lines have resulted in increased "naturalness" and intelligibility of the received speech, and further improvements have already been made in this direction. The introduction of loud-speaking telephones may also create a further demand for high quality

transmission. A very high degree of perfection is, of course, technically possible, but it must be remembered that the greater the perfection required the greater is the cost involved in attaining it.

Intelligibility and Articulation Efficiency. A telephone user in general passes information over a telephone connection by sentences and therefore 'sentence intelligibility' is perhaps the true test of quality of transmission, but it is affected by so many personal factors that it has not in the past been found practical as a standard to employ for actual measurements. A useful standard is found in 'syllable articulation efficiency,' which is used as a final test of telephone efficiency. It is, however, by no means easy to obtain reliable results on this basis, and it remains essentially a laboratory method of testing, requiring an experienced staff with a carefully acquired technique. The method employed is briefly as follows. At the sending end of the connection to be tested a speaker repeats into the transmitter syllables chosen at random. These syllables are composed of consonant, vowel and consonant, based on the esperanto alphabet, which are termed *logatoms*, lists of which have been prepared. A listener at the receiving end of the circuit records the syllables received in phonetic symbols and they are then compared with those transmitted. The percentage correctly received to the total number sent expresses the articulation efficiency of the connection.

Another method of measuring articulation efficiency is now coming into use, particularly in the United States. It is known as *repetition rate testing*. By this method normal calls are observed, and the number of repetitions which the subscribers find it necessary to make during conversation are noted, from which the percentage efficiency of the instruments is assessed. The method appears to be essentially a test of sentence intelligibility. Such tests must, in the nature of things, be long and laborious, much more so than syllable articulation tests. This articulation efficiency is effected by three principal factors, or sets of factors. They are—

(*a*) The volume of speech received, which is a factor combining the electro-acoustic efficiency of the instruments, the conditions under which they are used, and the transmission equivalent of the lines connecting them.

(*b*) Any distortion effects, the most important being attenuation distortion, to which transmitters, receivers and lines all contribute. This, of course, includes a consideration of the

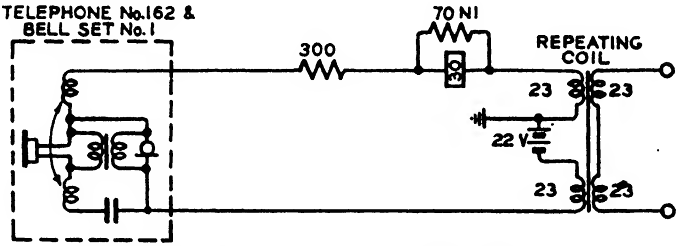

FIG. 385. PRACTICAL TRANSMISSION STANDARD OF BRITISH POST OFFICE

frequency band width transmitted. Phase distortion has a small effect and has already been discussed in Chapter XVI.

(*c*) Interference effects, including side tone, noise, echo and cross-talk.

Strictly speaking the three factors, (*a*), (*b*) and (*c*), are not independent of one another in their effect upon articulation efficiency, but by setting practical limits to any two of them the third can be considered separately.

Volume Efficiency and Reference Equivalent. Dealing first with the telephone instrument, the practical standard of refer-

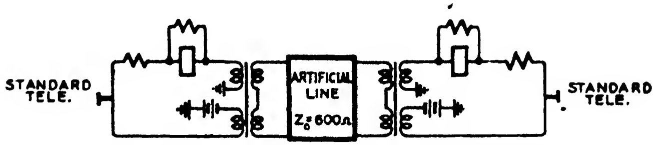

FIG. 386. STANDARD TRANSMISSION CIRCUIT

ence adopted by the British Post Office is provided by the performance of a C.B. telephone (P.O. Telephone No. 162 and Bell-set No. 1) connected by a 300-ohm non-inductive line to a 22-volt repeating coil cord circuit as shown in Fig. 385.

If two such circuits are joined together a standard transmission circuit is obtained, and by including an artificial line as shown in Fig. 386 (a characteristic impedance of 600 ohms is used), it provides a means of measuring the volume efficiency of any other transmission circuit.

The loss in the artificial line is increased until the volume efficiency of the circuit is equal to that of the circuit to be measured. The loss in decibels which has been introduced when equal efficiency is obtained, expresses the efficiency of the circuit under test. The term 'reference equivalent' is used to relate the performance of a transmission system to the International Transmission Reference System which is described later, and therefore measurements which have been made by comparison with the practical transmission standard, as described, require the addition of a factor expressing the performance of the practical standard compared with the International Reference System. This equating factor is proximately 11·3 db. for the complete system, due to the practical standard being 6·8 db. worse than International Reference on sending, and 4·5 db. worse than reference on receiving. When measurements are actually made in this way it is necessary to introduce an additional loss into both the standard circuit and the measured circuit so that the reference equivalent, as measured, shall not be less than about 15 db., and preferably of the order of 24 db., in order to eliminate errors due to reflection effects and to give the most suitable volume for measuring. Individual telephones, transmitters, and receivers can all be compared with standard instruments and their volume efficiency expressed in decibels, better or worse than standard, by means of the standard transmission circuit. A suitable switching scheme is, of course, required to make the test, depending upon which piece of apparatus is to be measured.

Turning now to the relation between reference equivalent and intelligibility it is found that, for the average conditions obtaining during ordinary telephone calls, an articulation efficiency of about 70 per cent is obtained with standard telephones and zero loss between the cord circuits. If a loss is introduced between the instruments, the articulation efficiency does not deteriorate appreciably until over 25 db. are inserted. If, however, the loss is further increased, intelligibility begins to fall rapidly. (See Fig. 387.) The maximum loss allowed between telephones, and the way in which this loss is distributed between local lines, junction, and trunk circuits, is dealt with later.

The manner in which the telephone is used has a great

effect upon the reference equivalent. Speaking into the transmitter with the lips at about 0·4 in. from the mouthpiece can be regarded as the normal manner. If the distance is increased to 0·75 in., the reference equivalent is reduced by about 4 db.

Distortion Effects. The attenuation distortion introduced by commercial telephone instruments within the effective speech

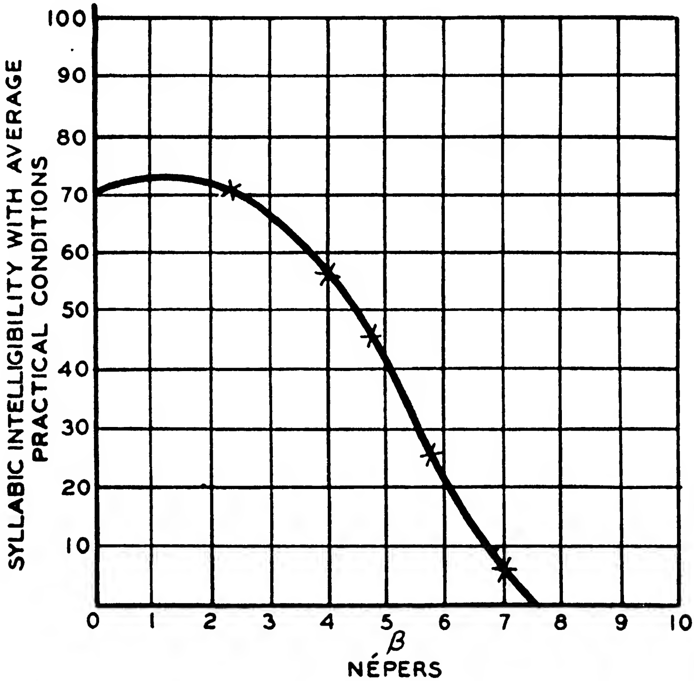

FIG. 387. SYLLABIC INTELLIGIBILITY PLOTTED AGAINST LOSS FOR AVERAGE PRACTICAL CONDITIONS

frequency band is very considerable, but in some ways this is partly intentional in the interest of maximum sensitivity. Transmitters and receivers are designed so that the mechanical and acoustical resonances will produce maximum sensitivity at a point in the frequency range where it will be most useful, that is, between frequencies of about 1 000 and 1 500 per sec. Typical frequency characteristics of a transmitter and receiver are shown in Figs. 16 and 20. The articulation efficiency obtainable with ordinary telephone instruments is about 20 per

cent less than that obtained with distortionless apparatus, as indicated by the maximum value of the curves in Fig. 388.

Long lines introduce attenuation distortion principally by the cut-off effect which restricts the frequency band transmitted. Fig. 388 shows the way in which articulation efficiency is affected by the elimination of high frequencies. It is seen that there is very little improvement to be obtained by extending the frequency band above 2 600 per sec., although by

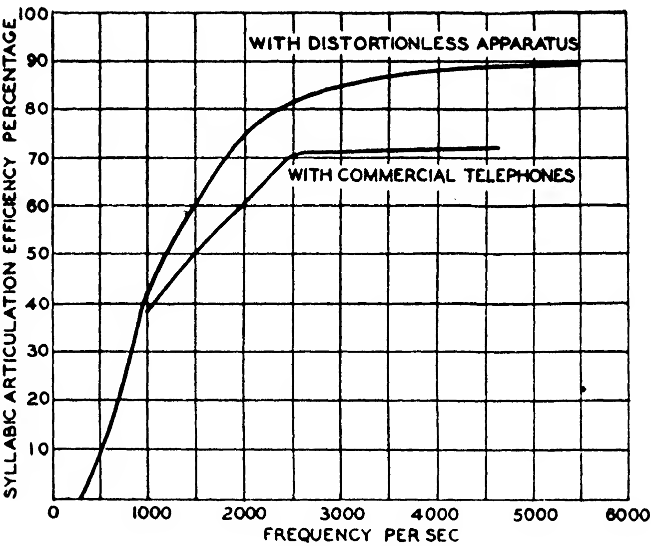

FIG. 388. EFFECT ON ARTICULATION EFFICIENCY OF CUTTING OFF THE HIGHER SPEECH FREQUENCIES

doing so the 'naturalness' of the reproduced speech can be very considerably improved. The present tendency is to give a frequency band of 300 to 3 000 per sec. on all circuits, audio, and carrier.

The other form of linear distortion, namely phase distortion, is introduced principally by loaded lines at frequencies near the cut-off. It is responsible for the phenomenon of *building-up-time* of signals which has, however, but a small effect on articulation efficiency. This has been dealt with in Chapter XVI.

Interference Effects. Disturbing noises can be introduced into a telephone connection by many causes, such as side tone, room noises, echo, cross-talk, induced voltages from power

lines, and noises introduced by amplifier power plant, etc. The effect of disturbing noise on the articulation efficiency depends very largely upon the nature of the disturbing noise. For example, a tone such as might arise by induction of a power system will have a much smaller effect than a disturbing noise of the same power arising from, say,. 'frying' in a bad transmitter.

Noise reduces the articulation efficiency of a circuit by

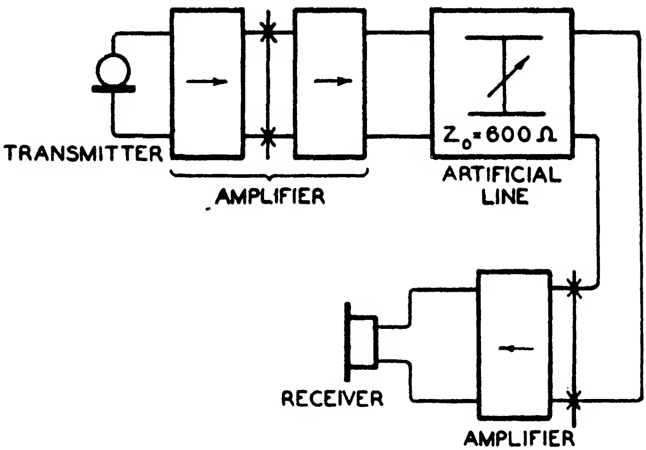

FIG. 389. SCHEMATIC DIAGRAM OF MASTER REFERENCE SYSTEM

masking some of the frequency bands comprising the speech sounds.

A method of assessing the effect of noise upon articulation known as the 'equivalent impairment method' has been used with some success. The method, briefly, is to assess the change in reference equivalent of a connection without the noise interference which will give the same reduction in articulation efficiency as does the noise. Fig. 390 shows curves constructed from such tests, the noise interference used being 0·5 mV. of power hum and 0·1 mV. frying noise.

International Reference Standard. An international standard of transmission is provided by the European Master Telephone Transmission Reference System (referred to as the S.F.E.R.T.) located in Paris, which was set up in 1928, and which is a replica of the American Master Reference System. It provides a fundamental basis which is rigorously defined in terms of

physical standards; for example, the performance of the transmitter is defined in volts generated per dyne per cm.^{2} air pressure acting on the diaphragm. By the aid of this international standard the practical transmission standards adopted by the various telephone administrations can be compared,

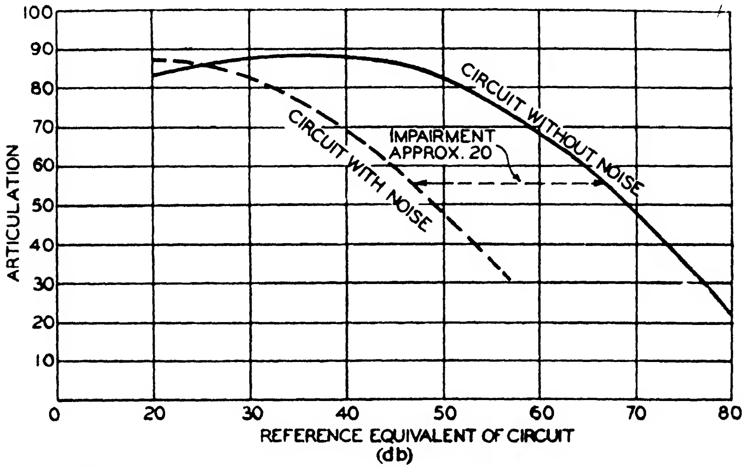

FIG. 390. CURVE SHOWING THE EFFECT ON ARTICULATION OF NOISE COMPOSED OF 0·5 mV. HUM PLUS 0·1 mV. FRY

and recommendations made for the design of transmission networks.

The apparatus comprises three essential parts (see Fig. 389)—

(*a*) A condenser transmitter with an associated amplifier and distortion correcting network.

(*b*) An artificial line of variable attenuation with a characteristic impedance of 600 ohms. This serves to balance the reference system against the system under test. In practice a fixed loss network is also inserted so that measurements are not made on a reference equivalent less than about 20 db.

(*c*) A moving-coil receiver and an associated amplifier.

The complete system is practically distortionless between frequencies of 100 per sec. and 7 000 per sec. and free from noise interference.

From this international reference system the national standards are calibrated. The British Post Office has a primary reference system which is practically identical with this. The calibration of a practical standard against a primary reference

standard is a matter of some difficulty due to the presence of distortion and noises in the former. The differences in tone particularly may result in discrepancies in the results obtained by even experienced transmission testing crews. The reference equivalent of the P.O. standard transmission circuit in terms of the primary reference system has already been quoted.

Sending and Receiving Allowances. The ordinary carbon transmitter can be regarded as an alternator which transforms the mechanical energy of sound waves into alternating speech currents. It has been shown in Chapter II that the magnitude of the speech currents is proportional to the value of the direct current supplied to the transmitter, and it is therefore desirable that this current should be as large as possible provided that it is not so large as to cause the transmitter to produce 'frying' noises; which is due to arcing between the carbon granules. A current of about 100 mA. is normally worked to as a maximum.

With a common battery telephone, which is the type now almost universally employed, the direct current is supplied to the transmitter from the exchange, and the line connecting the instrument with the exchange therefore affects the transmission efficiency in two ways.

(1) The direct current resistance of the line reduces the current flowing into the transmitter and this reduces the value of the speech currents generated.

(2) The speech currents generated by the transmitter are attenuated by the line. The received transmission is affected only by the transmission loss introduced by the line.

If the telephone is connected directly to the cord circuit these sending and receiving losses are of course eliminated, and the terms *sending allowance* and *receiving allowance* are therefore used to express a reduction in transmission efficiency caused by the local line. These terms should not be confused with the term *reference equivalent*; they merely express the improvement in transmission which could be effected by reducing the local line to zero.

With the local battery telephone the current supplied to the transmitter is not affected by the local line, and the sending allowance is therefore equal to the receiving allowance, that is, to the transmission loss caused by the line. With a central

battery telephone the sending allowance is equal to the receiving allowance plus the current reduction loss caused by the ohmic

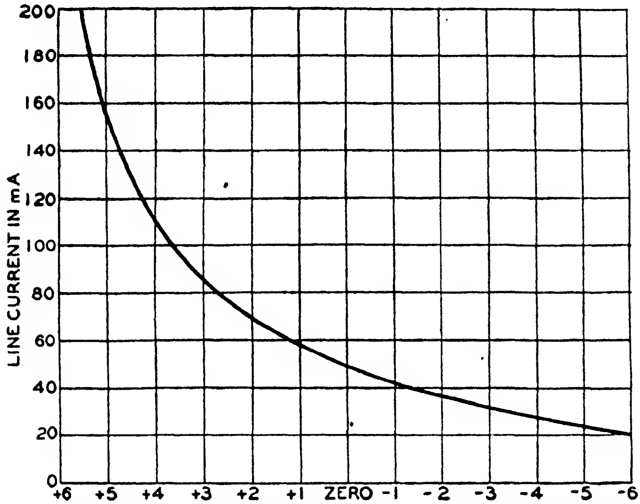

FIG. 391. TRANSMITTER CURRENT-EFFICIENCY CURVE
Telephone P.O. No. 162.

resistance of the line. In Fig. 391 the efficiency of a standard telephone connected to a 22-volt cord circuit by a variable resistance, relative to the standard telephone circuit, is plotted

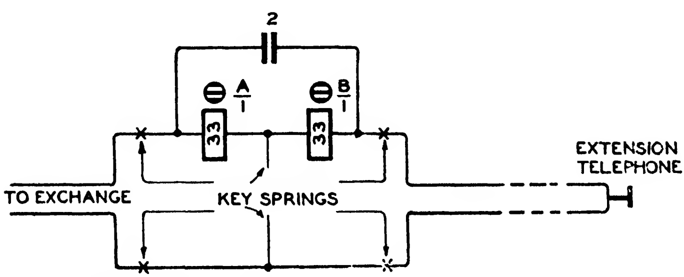

FIG. 392. P.B.X. APPARATUS INTRODUCED IN SERIES WITH AN EXCHANGE TO EXTENSION CALL

against transmitter current in milliamperes, and in Fig. 393 the sending and receiving allowances for a Telephone No. 162 connected to a 22-volt cord circuit by a variable line of pure resistance are plotted against line resistance. It is seen that

with a 300-ohm line the sending allowance is approximately 7·8 db. Similar sending and receiving allowance curves have also been constructed for various types of conductor used for subscribers' lines and for the various cord circuit voltages.

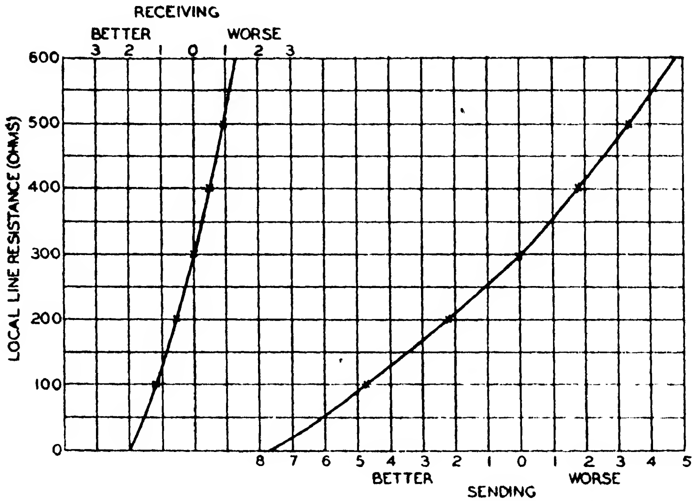

FIG. 393. SENDING ALLOWANCE AND RECEIVING ALLOWANCE CURVES
P.O. Telephone No. 162 connected to a 22-volt C.B. cord circuit.

Local Line Limits. For central battery instruments the Post Office requires that not less than 95 per cent of subscribers' installations shall provide a quality of transmission of not worse than that provided by the standard telephone circuit. For economic reasons a certain tolerance is allowed for the remaining 5 per cent. Since the attenuation of the local line is responsible for only a small proportion of the sending allowance, the fact that different types of line conductor are used is neglected and local line limits are stated simply in terms of resistance, depending upon the type of transmission bridge in the exchange equipment. Fig. 394 shows several examples of bridges and the respective line limits which may be used with them. The increased line resistances which may be allowed when low resistance relays and ballast resistances are included (Fig. 394 (*c*)) should be particularly noted. Where several different types of bridge may be connected to a subscriber's line for different classes of call, the lowest line resistance

limit appropriate to the respective bridges is used when planning local lines.

The tolerance allowed in the case of not more than 5 per cent of subscribers' lines is also stated in terms of resistance. An

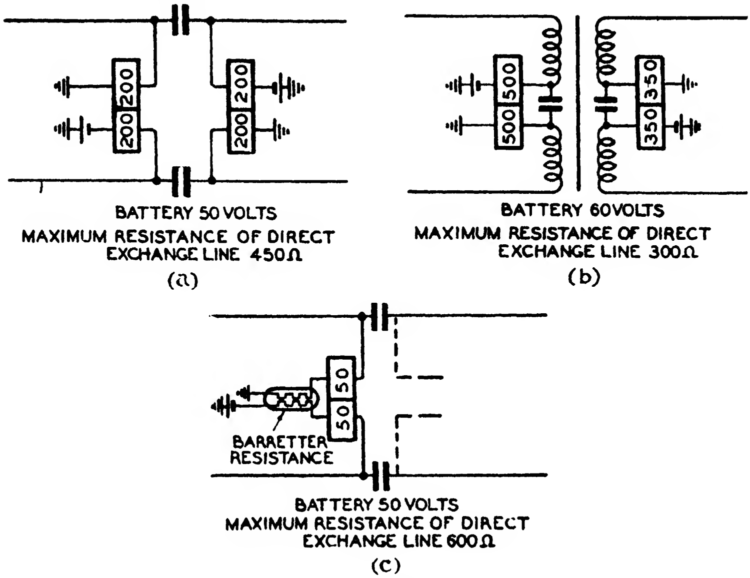

FIG. 394. THREE TYPES OF TRANSMISSION BRIDGE AND THEIR RESPECTIVE EXCHANGE LINE RESISTANCE LIMITS

additional 50 ohms is allowed except where the transmission bridges in the exchange have 50-ohm relays and barretter resistances, in which case no tolerance is allowed. In the case of an extension instrument at a subscriber's premises, for which a C.B. telephone is provided, the resistance of the extension line and of any apparatus at the main instrument or switchboard, which is in series with the line, must all be included in the maximum line resistance. An example is shown in Fig. 392.

For a local battery telephone connected to a C.B.S. type of exchange, the same transmission standard is required as for a C.B. telephone, but the local lines are designed to give this standard with the local primary battery in average condition. Since the local line is responsible for a transmission loss only, higher line resistance limits can in general be used than are

possible in the case of C.B. instruments, especially when three primary cells are used in the local battery. The highest limits determined by transmission requirements only cannot, however, always be used on account of signalling difficulties. For this reason an absolute limit of 500 ohms is fixed, and even this is not used in the case of an exchange which will ultimately be converted to automatic working, and for which a limit of 450 ohms will be required.

As in the case of C.B. telephones, the line limits for local battery telephones are stated in terms of ohmic resistance, but in this case different figures are used for different types of line conductors, as shown in Table 9.

TABLE 9

LINE RESISTANCES TO SECURE THE STANDARD GRADE OF TRANSMISSION WITH L.B. TELEPHONES

(with battery in average condition)

Subscriber's Instrument		No. of Cells	Repeating Coil Bridges at the main Exchange				Stone Bridges at the main Exchange			
			Maximum Line Resistance to meet Standard Grade of Transmission							
Telephone	Bell-set No.		Aerial Wire	Cable 6½ lb.	Cable 10 lb.	Cable 20 lb.	Aerial Wire	Cable 6½ lb.	Cable 10 lb.	Cable 20 lb.
Microtelephone with Transmitter Inset No. 10 or Telephone with Transmitter No 22	5, 6, 15, 29	2	125	125	125	100	200	175	175	150
		3	525	500	425	375	625	575	475	450
	21	2	475	425	350	325	575	500	425	375
		3	725	600	475	425	850	700	550	500

It is sometimes necessary to use local battery telephones on lines connected to a C.B. exchange, where it would be uneconomical to provide sufficiently heavy conductors to meet the appropriate line limits for the C.B. exchange, and a line resistance table similar to Table 9 is available to meet these cases. Table 9 is not used for this purpose because it is designed, as already stated, to ensure standard grade of transmission with a local battery in average condition, whereas standard grade of transmission is required for a local battery telephone connected to a C.B. exchange with the local battery in the worst condition that is likely to be experienced in practice.

Zone and Group System. For the proper routing of trunk calls to ensure a satisfactory standard of transmission, and to give a standard operating procedure, the country is divided into zones which are further subdivided into groups. Fig. 395

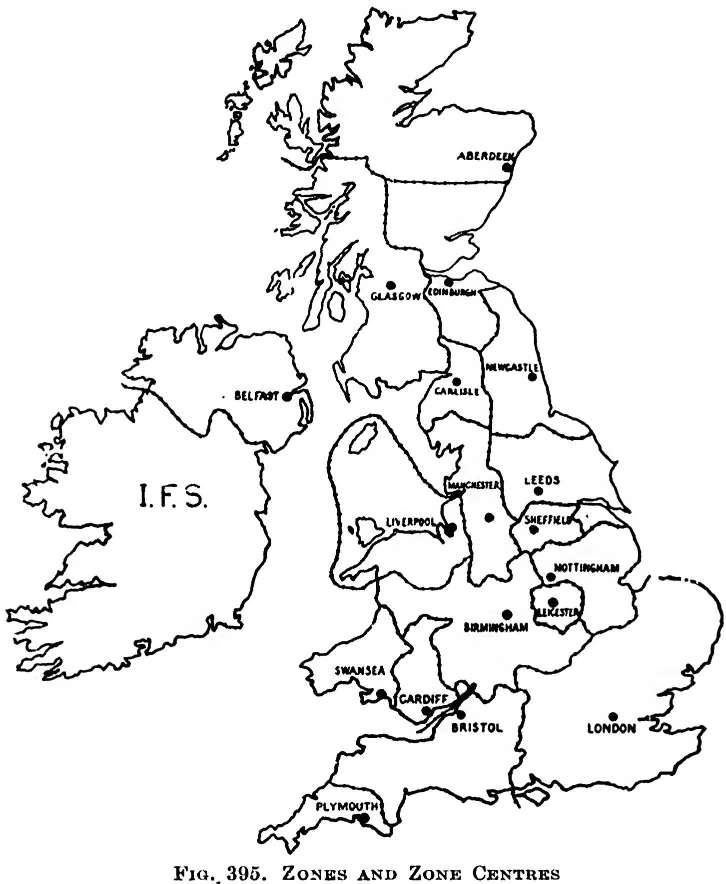

FIG. 395. ZONES AND ZONE CENTRES

shows the zones with the zone centre exchanges marked, and Fig. 396 shows the group and group centre exchange for eight of these zones. The zone centres are interconnected by zero-loss trunk circuits, and the group centres are connected by circuits of somewhat lower transmission equivalent to their respective zone centres. Some important group centres are also connected to the zone centre exchange in other zones by circuits

of a grade similar to the group to zone circuits. Within the groups themselves there are three types of exchanges. These are—

(*a*) Group centre exchanges.

(*b*) Minor exchanges which are connected by direct circuits to the group centre.

(*c*) Dependent exchanges which are not connected by direct

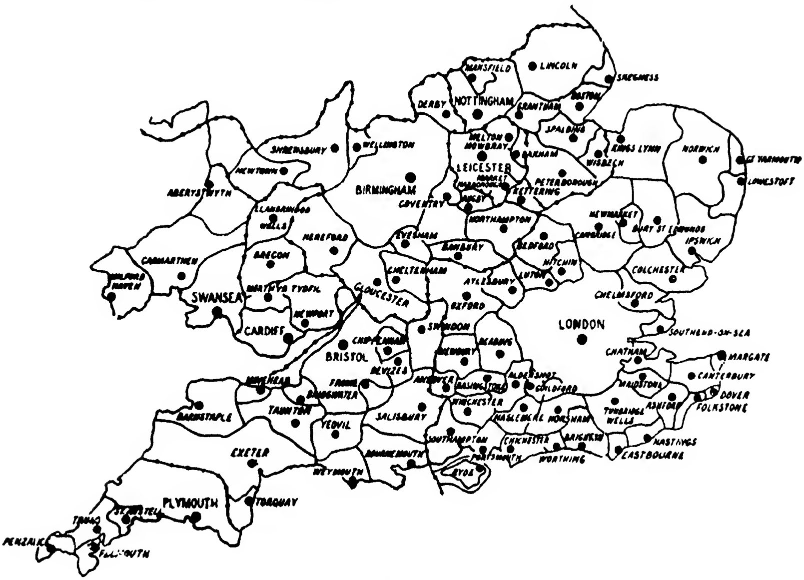

Fig. 396. Zone and Group Centres

Zone centre boundaries are indicated by dotted lines; group centre boundaries by continuous lines.

circuits to the group centre, but are dependent for junction and trunk calls upon a minor exchange.

In general it can be stated that direct circuits are provided between any two exchanges when there is sufficient traffic to justify this, but the provision of such direct circuits depends very largely on the availability of line plant. Since only a very small proportion of subscribers' lines are connected to dependent exchanges, most trunk calls can be set up by the methods of routing shown in Fig. 397. In exceptional cases where it is required to connect a subscriber on a dependent exchange to a subscriber on another dependent exchange, one of the methods

of routing shown in Fig. 397 is necessary, but these can be regarded as exceptional conditions.

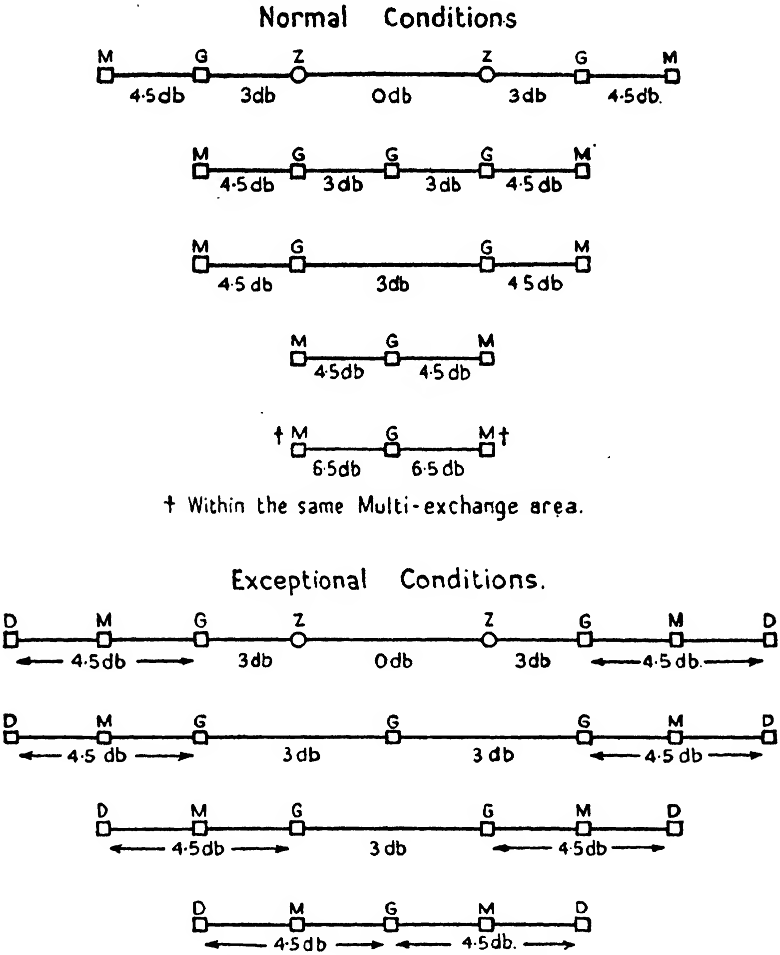

FIG. 397. TRANSMISSION LOSSES

Z = Zone centre. *G* = Group centre. *M* = Minor exchange. *D* = Dependent exchange.

Transmission Standards for Trunk and Junction Circuits. The British Post Office aims at a trunk and junction system designed so that a call between any two telephones shall provide a standard of transmission not worse than that given by two standard telephones connected by 300-ohm non-inductive lines

to 22-volt cord circuits and with a 15-db. loss between these cord circuits. As already stated, the subscribers' lines are designed so that standard transmission is given by at least 95 per cent of subscribers' lines, and therefore the loss between the local exchange to which a calling subscriber is connected, and the exchange to which the called subscriber is connected, must not exceed 15 db. in order to give the above standard of transmission; i.e. the overall connections as shown in Fig. 397 must not represent a loss greater than 15 db. It is, of course, possible to obtain reliable speech over a much higher loss if the conditions under which the telephones are used are good.

Notwithstanding the very high cost of long distance circuits, the shorter circuits connecting dependent to minor exchanges and minor to group centre exchanges, due to their greater number, involve a total expenditure several times as great as that of the long distance circuits. If, therefore, it can be arranged at reasonably small cost to reduce the overall transmission loss on the longer lines, considerable savings can be effected in the cost of the shorter circuits. The modern improvements in cables and amplifiers have enabled this saving to be achieved.

As far as possible the total transmission losses are divided between the various types of circuits as shown below.

	Loss (db.)
Zone to zone centre circuits	zero
Zone centre to group centre circuits	3·0
Zone centre to group centre in another zone	3·0
Group centre to group centre circuits	3·0
Group centre to minor exchange circuits	4·5
Group centre to dependent exchange via minor exchange	4·5
Group centre to minor exchange in multi office area	6·5
Direct circuits between any two exchanges (not used as links for long distance connections)	12·0

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